34
Economic Analysis of Power Plants and Tariffs

34.1. INTRODUCTION

The engineering thermodynamics always emphasizes for the maximum efficiency of the plant that can be theoretically obtained for the given conditions. This emphasis gives a strong bias to the engineers in favour of most efficient equipment. The power plant design must be made on the basis of most economical condition and not on the most efficient condition as profit is the main basis in the design of the plant and its effectiveness is measured financially. The main purpose of design and operation of the plant is to bring out the cost of energy produced to minimum. The efficiency of the plant is one factor among many that determines the energy cost. Unfortunately, in majority of cases, the most thermally efficient plant is not economic one.

34.2. COST OF ELECTRICAL ENERGY

The cost of the electrical energy generated consists of fixed cost and running cost.

(A) Fixed Cost. The fixed cost is the capital invested in the installation of complete plant. This includes the cost of land, buildings, equipments, transmission and distribution lines, cost of planning and designing the plant sub-stations and many others. It further includes the interest on the invested capital, insurance, maintenance cost and depreciation cost.

1. Land Building and Equipment Cost. The cost of land, building, does not change much with different types of plants but the cost of equipment changes considerably. The cost of the equipment or the plant investment cost is usually expressed on the basis of kW capacity installed. The capital cost per kW installed capacity does not change much for thermal plant but it changes a lot in case of hydro-plants. Because the cost of hydro-plant depends upon the foundation available, type of dam and spillways used, available head and quantity of water. The capital cost of hydroplant may vary from Rs. 18000/kW to Rs. 30000/kW. The capital cost of thermal-plant is about Rs. 10000/kW on the basis of 1970.

2. Interest. The interest on the capital investment must be considered because otherwise if the same capital is invested in some other profitable business could have equal the interest considered. A suitable rate of interest must be considered on the capital invested.

3. Depreciation Cost. It is the amount to get aside per year from the income of the plant to meet the depreciation caused due to wear and tear of the equipments. The capital investment for the plant installation must be recovered by the time the life span of the plant is over, so that it can be replaced by a new plant. Some amount from the income is set aside per year as depreciation cost of the plant which accumulates till the plant is in operation. The amount collected by way of depreciation by the time the plant retires is equal to the capital invested in the installation of the plant.

Different methods are used for finding out the depreciation cost of the power plant. Few of them which are commonly used are listed below :

(*a*) Straight line method
(*b*) Sinking fund method
(*c*) Diminishing value method.

P = Initial investment to install the plant.

S = Salvage value at the end of the plant life.

n = Life of plant in years.

r = Annual rate of compound interest on the invested capital.

A = The amount set aside per year for the accumulation of the depreciable investment at the end of nth year.

(*a*) **Straight Line Method.** According to this method, annual amount to be set aside is calculated by using the following formula :

$$A = \frac{P-S}{n}$$

In this method, the amount set aside per year as depreciation fund does not depend on the interest it may draw. The interest earned by the depreciation amount is taken as income.

This method is commonly used because of its simplicity.

(*b*) **Sinking Fund Method.** In this method, the amount set aside per year consists of annual instalments and the interest earned on all the instalments. This method is based on the conception that the annual uniform deduction from income for depreciation will accumulate to the capital value of the plant at the end of life of the plant or equipment. A is the amount set aside at the end of each year for n years, then

Amount set aside at the end of first year $= A$

Amount at the end of second year $= A + \text{interest on } A = A + Ar = A(1 + r)$

Amount at the end of third year $= A(1 + r) + \text{interest on } A(1 + r)$

$= A(1 + r) + A(1 + r)r$

$= A(1 + r)^2$

$\therefore$ Amount at the end of nth year $= (1 + r)^{n-1}$

Total amount accumulated in n years

$$= \text{Sum of the amounts accumulated in } n \text{ years}$$

$$y = A + A(1 + r) + A(1 + r)^2 + ... + A(1 + r)^{n-1}$$

$$= A[1 + (1 + r) + (1 + r)^2 + ... + (1 + r)^{n-1}] \qquad ...(1)$$

Multiplying the above equation by $(1 + r)$, we get

$$y(1 + r) = A[(1 + r) + (1 + r)^2 + (1 + r)^3 + ... + (1 + r)^n] \qquad ...(2)$$

Subtracting Equation (1) from Equation (2), we get

$$y \cdot r = [(1 + r)^n - 1]A$$

$$\therefore \quad y = \left[\frac{(1 + r)^n - 1}{r}\right]A$$

where $y = (P - S)$

$$\therefore \quad (P - S) = \left[\frac{(r + 1)^n - 1}{r}\right]A$$

$$\therefore \quad A = \left[\frac{r}{(1 + r)^n - 1}\right](P - S)$$

(*c*) **Diminishing Value Method.** In this method, the amount set aside per year decreases as the life of the plant increases. This can be explained by the following example :

Say the equipment cost is 20000 Rupees. The amount set aside is 10% of the initial cost at the beginning of the year and 10% of the remaining cost with every successive year. Therefore

The amount set aside during first year

$$= 20000 - \frac{10}{100} \times 20000 = 18000 \text{ balance}$$

The amount set aside during second year

$$= 18000 - \frac{10}{100} \times 18000 = 18000 - 1800 = 16200 \text{ balance}$$

The next instalment during third year

$$= 16200 - \frac{10}{100} \times 16200 = 14580 \text{ balance.}$$

This method requires heavy instalments in the early years when the maintenance charges are minimum and it goes on decreasing as the time passes but the maintenace charges increase. This is the main disadvantage of this method.

4. Insurance. It becomes necessary many times to insure the costly equipments specially for the fire risks. A fixed sum is set aside per year as insurance charges. The annual premium may be 2 to 3% but the annual instalment is quite heavy as the capital cost of the plant is considerably high.

5. Management Cost. This includes the salaries of the people working in the plant. This must be paid whether the plant is working or not. Therefore, this is included in fixed charges of the plant.

(B) Operating Costs. The operating cost of the electrical power generation includes the cost of fuel, cost of lubricating oil, grease, cooling water and number of consumable articles required. The wages required for supplying the above material are also included in the operating cost of the power plant.

1. Fuel Cost. The fuel cost is proportional to the amount of energy generated. The rate of fuel consumption per unit of energy generated also varies according to the load on power plant. The consumption on fuel per unit of energy generated is minimum at full load on power plant because the prime-mover works at maximum efficiency at full load conditions.

2. Oil, Grease and Water Cost. The cost of these materials is also proportional to the amount of energy generated. This cost increases with an increase in life of the power plant as the efficiency of the power plant decreases with the age.

The total cost of energy produced is the sum of fixed charges and operating charges. The common way of representing the cost of power plant is given below :

$$C = x \text{ Rupees/kW} + y \text{ N.P./kW-hr.}$$

34.3. SELECTION OF TYPE OF GENERATION

Because power supply comes from a utility which is financed by central government, the objective of electric-generation investment must be optimum or most efficient use of national resources.

Once the total energy needed per year and peak demand are known, the problem of selecting the type of generation arises. Theoretically this could be achieved by steam power plant, hydroelectric power plant, nuclear power plant, diesel power plant or gas turbine power plant. The elimination of some of these alternatives is done on the basis of other controlling factors such as non-availability of water power sites, inability to obtain ceratin fuels at economic prices at a proposed site, lack of large water supply required for steam power plants and many such factors without going into economic cost considerations.

The points which are to be considered in choosing the type of generation are listed below :

(1) The type of fuel available or availability of suitable sites for water power generation.

(2) The cost of transmitting the energy.

(3) The cost of fuel transportation.

(4) The cost of the foundation and land required.

(5) The availability of an adequate supply of cooling water.

(6) The type of load to be taken by the power plant.

(7) Reliability in operation.

(8) The life of the plant.

Once the type of generation is decided according to the potential availabilities, the next work to the designer is to choose the generating equipments whose cost would be minimum.

In the electric power plant, the capital cost of the generating equipments increases with an increase in efficiency. In case of steam power plant, a choice may be made on the basis of a cycle used such as Rankine cycle or cycle with five stages of regenerative feed heating or cycle with five stages of regenerative feed heating with one stage of reheating.

The capital investment increases with an increase in cycle efficiency and the fixed cost increases directly with an increase in capital investment. The increase in fixed cost per kW installed capacity with an increase in efficiency of the plant (increase in capital investment) is shown in Fig. 34.1.

The benefit of such increase in the capital investment will be realised in lower fuel costs as the consumption of fuel decreases with an increase in cycle efficiency. Therefore, the operating cost (C_0) decreases with increase in thermal efficiency (increase in capital cost) as shown in Fig. 34.1.

To study the trend of the total annual cost C_t ($C_t = C_f + C_o$), the two major components costs C_f and C_o are plotted on a common graph as shown in Fig. 34.1. Adding these two components at any given investment (cycle efficiency) determines the characteristic of the total annual cost C_t.

In case of inefficient plant of low investment cost ; the operating cost is major cost in the total cost, whereas for highly efficient plants, the fixed cost becomes major item. The total cost becomes minimum at some intermediate value of investment.

The total cost becomes minimum when the slope of the total cost curve becomes zero.

$$\therefore \quad \frac{dC_t}{dP} = 0$$

$$\frac{d}{dP}(C_f + C_o) = 0$$

$$\therefore \quad \frac{dC_f}{dP} = -\frac{dC_o}{dP}$$

or when the slopes of the fixed cost curve and operating cost curve become equal in magnitude but opposite in sign. This does not happen necessarily where the two cost components are equal.

It is the prime duty of the designer to produce the energy at the lowest possible price. In electric generating systems, the fundamental way to compare alternate schemes of power generation is to compare their total annual costs.

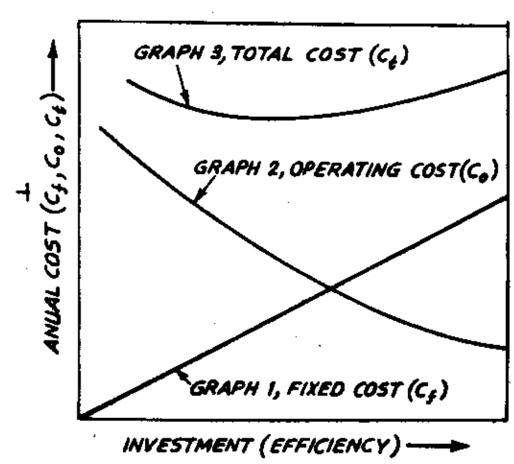


Fig. 34.1. Variation of fixed and operation costs *versus* investment.

The diesel power plants have the advantages of operating at higher thermal efficiencies than the steam power plants, specially in smaller capacity range. The maximum capacity of diesel plant is much smaller than steam plant or hydro-plants. The maximum capacity of 30 MW diesel unit has been installed in Europe where the 800 MW capacity units are common for thermal and hydraulic plants. Owing to this vast difference in capacity and aided by the fact that coal is usually cheaper than oil, the diesel plants have not found much applications in large power supply system except as a temporary expedient.

The usual procedure to measure the usefulness and economic possibilities of a proposed hydraulic plant is by comparing its total annual costs with those of an alternate steam plant having the same firm capacity. The fuel cost in large steam plant is often 50% of its total annual cost and remaining is fixed cost. In hydraulic power plant, the operating cost is a small part of its total annual cost, therefore, it is economical to invest a greater amount initially, relative to the thermal plant, provided that the hydraulic plant can produce sufficient energy to serve the load at all times when it is needed.

In most hydro-electric power plants, the installed plant capacity in excess of the capacity available in river flow at the time of *peak load is always preferable. The installed capacity may be equal to or less than the maximum run-off. In this case, whenever the water flow is of sufficient magnitude, the hydro-generated energy will displace some generation at the thermal plant and save the fuel.

34.4. SELECTION OF GENERATING EQUIPMENTS

It has been seen that the load on the power plant does not remain constant owing to variable demand during the day by the consumers. The variation is greater with a low load factor. The minimum generating capacity of the plant must be equal to the maximum demand. If an interruption of service can be tolerated at any time, then the capacity equal to peak or maximum demand may be placed in one generating equipment. In this case, the prime-mover and generator would be working at full load only for short period of a day. When the load factor is comparatively low, the single unit supplying the power will be running under most uneconomical conditions for the considerable period of the day. This is because, the overall efficiency of generation is lower at lower load factor.

In most cases, an interruption of service cannot be tolerated as the stoppage of some industrial processes may cause costly spoilage and life hazard in ventilation systems used in mines. Therefore, it is necessary for a power station to maintain reliability and continuity of power supply at all times.

If this requirement is to be satisfied, another set of equal capacity must be installed for use when the first set is out of order or under repair. To use two units of equal capacity each being capable of supplying the maximum demand independently to maintain reliability is economical if the load is small and load factor is high. There is possibility of both machines being unavailable simultaneously, it will not justify the cost of installing the third unit, since the probability of such an occurrence is rather remote. The use of one unit only to supply the whole of the variable load is neither practical nor economical in large power supply systems where reliability of supply is essential.

The way of deciding the size and number of generating units in the power station is to choose the number of sets to fit the load curve as closely as possible. The number of generating units used must supply the peak load and keep the reserve capacity equal to one largest unit. The unit required for reserve capacity in this case would be much smaller than the maximum load capacity required in the last case. By increasing the number of generating units to supply the peak load, the building cost increases, the maintenance cost increases as more sets involve more starting, stopping and parallel operations of the units, the capital cost increases as the cost of single unit decreases with an increase in its capacity. A compromise must be made in the selection of size and number of units to avoid both the extremes mentioned above.

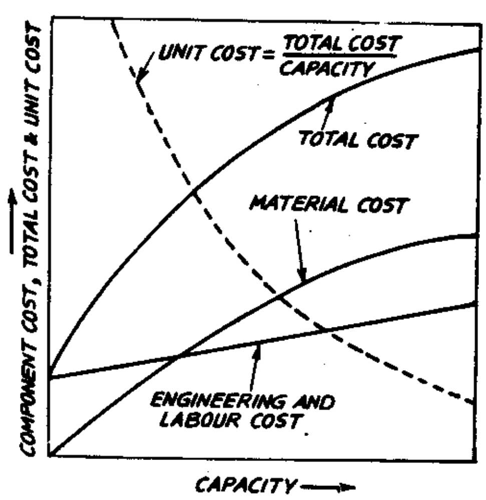


Fig. 34.2. Variation of costs of the Power Plant *versus* its capacity.

*The rate of water flow seldom reaches a maximum at the time of peak demand; *i.e.*, there is diversity between peak demand and peak rate of flow.

After selecting the size and number of units, allow them to work on suitable portions of the load curve in such a way that each will operate at about full load or the load at which it can give maximum efficiency.

The equipment prices are usually compared on the basis of price per unit of capacity, usually termed as 'unit price'. The unit price decreases as the capacity of the machine increases. This is the main reason for adopting a large size generating unit in power plants. Figure 34.2 shows the general trend and the trend of the major cost components in building a given type of machine.

The labour and engineering cost curve increases slightly with the capacity of the unit. The material cost curve decreases in slope with an increase in capacity of the unit. The total cost curve follows the pattern of material cost curve. The total cost curve shows positive intercept at zero capacity which represents the cost of just maintaining an organization of men and plant ready to produce. The curve 4 shows the reduction in unit price with an increase in capacity and this is the major argument for installing large units. The large units are always preferred for the loads with higher load factors (0.8 to 1).

34.5. PERFORMANCE AND OPERATING CHARACTERISTICS OF POWER PLANTS

The performance of generating power plants is compared by their average efficiencies over a period of time. The average efficiency of a power plant is the ratio of useful energy output to the total energy input during the period considered. This measure of performance varies with uncontrolled conditions such as cooling-water temperature, shape of load curve and quality of fuel. Therefore, it is not a satisfactory standard of comparison unless all plant performances are corrected to the same controlling conditions.

Plant performance can be precisely represented by the input-output curve from the tests conducted on individual power plant. The input-output can be represented as

$$I = a + bL + cL^2 + dL^3$$

where I is input expressed in millions of kJ per hour in case of thermal plants and in c.u.m. of water per second in case of hydroplants and L is the output or load either in MW or kW, a, b, c and d are constants.

The input-output curve for a power plant is shown in Fig. 34.3 (a). At zero load ($L = 0$), the positive intercept for I measures the amount of energy required to keep the plant in running condition. Any additional input over no-load input produces a certain output which is always less than input.

The efficiency of the power plant is defined as a ratio of output to input.

$$\therefore \qquad \eta = \frac{L}{I} = \frac{L}{a + bL + cL^2 + dL^3}$$

For any given load, the efficiency can be calculated with the help of the above formula. The efficiency curve (output versus efficiency) can be drawn as shown in Fig. 34.3 (b).

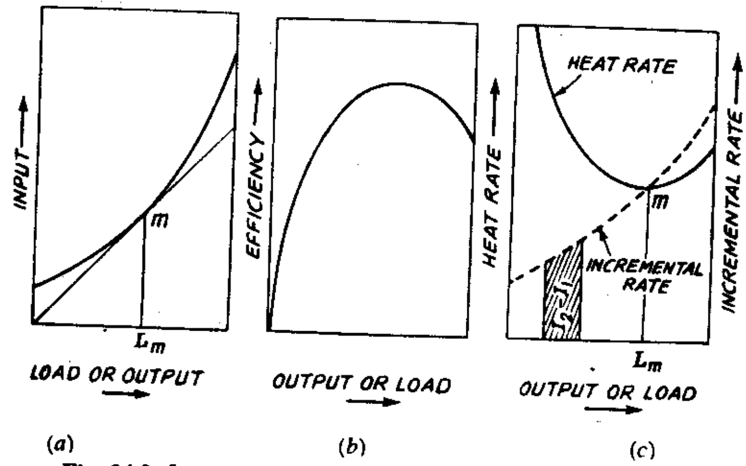


Fig. 34.3. Input-output curve and corresponding efficiency heat-rate and incremental-rate curves.

The heat rate curve and the incremental rate curve may be derived from the basic input-output curve. The heat rate is defined as the input per unit output.

$$\therefore \qquad HR \text{ (heat rate)} = \frac{I}{L} \text{ kJ/kW-hr}$$

$$= \frac{a + bL + cL^2 + dL^3}{L} = \frac{a}{L} + b + cL + dL^2.$$

The heat rate curve is derived by taking at each load the corresponding input. This curve is drawn as shown in Fig. 34.3 (c).

The relation between efficiency and heat rate is given by

$$\eta = \frac{1}{HR}.$$

The incremental rate is defined as the ratio of additional input (dI) required to increase additional output.

$$\therefore \qquad IR \text{ (incremental rate)} = \frac{dI}{dL} \text{ kJ/kW-hr.}$$

The incremental rate curve (L *versus* IR) is derived from the input output curve by finding at any load the additional input required for a given additional output and is drawn as shown in Fig. 34.3 (c). Mathematically the incremental rate is the slope of the input-output curve of the given load. The incremental rate expresses the amount of additional energy required to produce an additional unit of output at any given load.

From the above equation, we can write

$$dI = IR \, . \, dL$$

$$\therefore \qquad I_2 - I_1 = \int_{L_1}^{L_2} IR \, . \, dL$$

This indicates that the area under the incremental rate curve gives the total input to the plant to increase the output from L_1 to L_2.

The total input from no-load to full load is given by

$$I_f - I_o = \int_{L_o}^{L_f} IR \, . \, dL$$

where the suffix 'f' indicates full load and suffix '0' indicates no load on the power plant.

$$IR = \frac{dI}{dL}.$$

Substituting the value of I in the above equation,

$$IR = \frac{d}{dL}(a + bL + cL^2 + dL^3) = b + 2cL + 3dL^2.$$

This is known as incremental rate curve.

The incremental load curve can be considered a straight line for relatively small increase in output. This is not true for large increment of load because of the marked curvature of the incremental rate curve.

It is obvious from Fig. 34.3 (c) that the incremental rate curve crosses the heat rate curve at the lowest value of heat rate when both curves are plotted on the common coordinates. The reason for this is explained mathematically as given below :

At minimum heat rate, the slope of the heat rate curve must be zero.

$$\therefore \quad \frac{d}{dL}(HR) = \frac{d\,(I/L)}{dL} = 0 \text{ as } HR = \frac{I}{L}\,.$$

$$\therefore \quad \frac{LdI - IdL}{L^2} = 0$$

$$\therefore \quad LdI - IdL = 0$$

$$\therefore \quad \frac{dI}{dL} = \frac{I}{L}$$

$$\therefore \quad IR = HR \text{ when } HR \text{ is minimum.}$$

This indicates that the heat rate of continuous input-output curve is minimum when it equals the incremental rate. The incremental rate curve has a continuous increasing characteristic, therefore, two curves (HR versus load and IR versus load) must cross at load L_m when $IR_m = HR_m$.

From Fig. 34.3 (*c*), it can be stated that for the load between zero and L_m

$$IR < HR \text{ or } \frac{dI}{dL} < \frac{I}{L} \text{ or } \frac{I}{L} < \frac{I + dI}{L + dL}$$

For the loads above L

$$IR > HR \text{ or } \frac{dI}{dL} > \frac{I}{L} \text{ or } \frac{I}{L} > \frac{I + dI}{L + dL}\,.$$

In other words, starting from zero load, the relatively low rate of additional input per unit of additional output helps to decrease the heat rate as the load increases until the heat rate equals the incremental rate. After the minimum heat rate is reached, the increment rate causes a continuous rise in heat rate.

34.6. LOAD DIVISION

In the design of generating plants, the economy has been given prime importance. Engineers are designing the boilers, turbines, condensers, generators etc., most successfully to get the highest thermal efficiency of the plant. Number of methods have been introduced for the economic operation of the power plant at part loads and under variable load conditions. Transmission lines are also successfully designed to give minimum transmission losses.

The major problem for the power engineers is the economic distribution of the output of the generators. The proper division of load between two generators to give maximum overall efficiency is the major problem in load distribution among the generators.

Figure 34.4 (*a*) shows the input-output curves for two generators within a power-plant which are operating in parallel and supply a common load. The figure shows that the generator *A* is more efficient than *B* throughout its load range as the output of *A* is more than output of *B* for the same input. Therefore, it would be a common tendency to load *A* first to its full capacity and then load *B* for the remaining load. This is not proper distribution as the overall efficiency of the system would not be highest with the distribution of loads as mentioned above.

A method must be found out to load the generators to give the highest efficiency for the system.

The problem of dividing the load among the two generators for giving the maximum efficiency can be attacked by plotting the sum of the inputs of *A* and *B* against the load *A* for a given constant load on the two units. The graph for the above-mentioned loading is drawn as shown in Fig. 34.4 (*b*).

Say total load is 8 MW. If the load on $A = 0$ and on $B = 8$ MW, then the load on $A + B = 8$ MW. The required input for *A* and *B* can be calculated from Fig. 34.4 (*a*). If the load on $A = 2$ MW and on $B = 6$ MW then again the combined load supplied by $A + B = 8$ MW and the corresponding required input for this load division can also be calculated from Fig. 34.4 (*a*) and we can draw a curve 1 for total load of 8 MW corresponding to different outputs of *A* as shown in Fig. 34.4 (*b*). Such different curves for different constant value of ($L_a + L_b$) can also be drawn using the same procedure as described above. All these curves show one point where the combined input is minimum for the given total load. Corresponding to this point (say m_1) of minimum input to the system for the required output, we can find out the load on generator A. The load on the generator B is the difference between the total load and load taken by the generator A. This distribution of load is most economical as it requires minimum input for required load and gives highest efficiency of the system.

This method is not adopted in practice when the number of generators supplying the load are more than two because the application of the above principle becomes a cumbersome process.

The basic principle of economic load division is discussed below :

Considering any combined constant output, locus as shown in Fig. 34.4 (*b*), at the point of minimum input

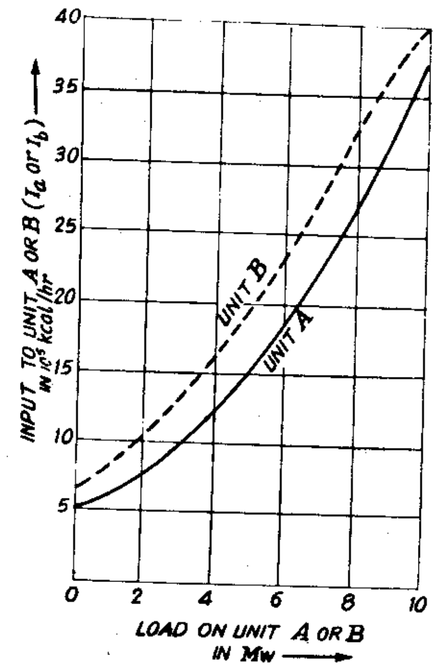


Fig. 34.4 (*a*). Input-output characteristics of units *A* and *B*.

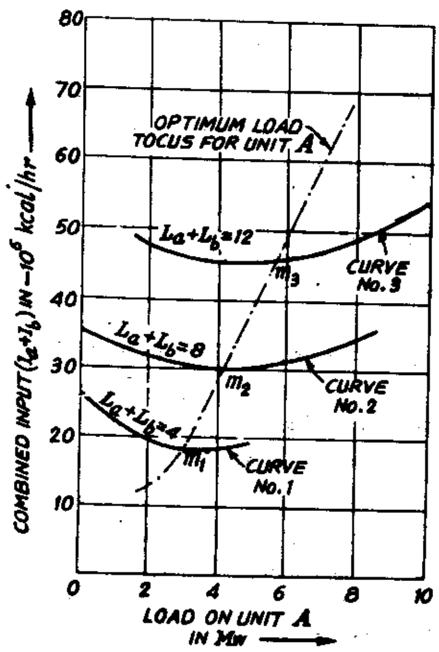


Fig. 34.4 (*b*). Variation of combined input with varying load division between units *A* and *B*.

$\therefore$ $$\frac{dI_e}{dL_a} = 0$$

where $I_e = I_a + I_b$ = combined input to A and B.

$L_c = L_a + L_b$ combined output of A and B.

$\therefore$ $$\frac{dI_e}{dL_a} = \frac{d_a}{dL_a}(I_a + I_b) = \frac{dI_a}{dL_a} + \frac{dI_b}{dL_a} = 0.$$

$\therefore$ $$\frac{dI_a}{dL_a} = -\frac{dI_b}{dL_a} \quad ...(1)$$

But $$\frac{dI_b}{dL_a} = -\frac{dI_b}{dL_a}\cdot\frac{dL_b}{dL_a} \quad ...(2)$$

But $$L_b = L_e - L_a$$

$\therefore$ $$\frac{dL_b}{dL_a} = \frac{dL_e}{dL_a} - \frac{dL_a}{dL_a}$$

where L_c is constant

$$\therefore \quad \frac{dL_b}{dL_a} = -1.$$

Substituting this value in Equation (2), we get

$$\frac{dI_b}{dL_a} = -\frac{dI_b}{dL_b} \quad ...(3)$$

Substituting the value of equation (3) into Equation (1), we get

$$\frac{dI_a}{dL_a} = -\frac{dI_b}{dL_b} \quad ...(4)$$

This is the condition for the minimum input for the combined constant output. Equation (4) indicates that for minimum combined input to carry a given combined output, the slopes of the input-output curves for each unit must be equal.

If there are n units, supplying a constant load, then the required condition for the minimum input or maximum system efficiency is

$$\frac{dI_1}{dL_1} = \frac{dI_2}{dL_2} = \frac{dI_3}{dL_3} = ... = \frac{dI_n}{dL_n} \quad ...(5)$$

34.7. TARIFF METHODS FOR ELECTRICAL ENERGY

The rates of energy sold to the consumers depend on the type of consumers as domestic, commercial and industrial. The rates depend upon the total energy consumed and the load factor of the consumer.

Whatever may be the type of consumer, all forms of energy rates must cover the following items :

(1) Recovery of capital cost invested for the generating power plant.

(2) Recovery of the running costs as operation cost, maintenance cost, metering the equipment cost, billing cost and many others.

(3) Satisfactory profit on the invested capital as the power plant is considered a profitable business for the government.

Although the determination of each cost item is simple but the allocation of these items among the various classes of consumers is rather difficult and requires considerable engineering judgement.

General Rate Form. The general type of tariff can be represented by the following equation :

$$z = a.x + b.y + c$$

where z = Total amount of bill for the period considered.

x = Maximum demand in kW.

y = Energy consumed in kW-hrs during the period considered.

a = Rate per kW of maximum demand.

b = Energy rate per kW-hr.

c = Constant amount charged to the consumer during each billing period. This charge is independent of demand or total energy because a consumer that remains connected to the line incurs expenses even if he does not use energy.

The various forms used for charging to the consumers as per their energy consumed and maximum demand are derived from the general formula as given above.

(1) Flat Demand Rate. This type of charging depends only on the connected load and fixed number of hours of use per month or year. This rate expresses the charge per unit of demand (kW) of the consumer. This system eliminates the use of metering equipments and manpower required for the same.

This can be expressed as

$$z = ax.$$

Under this system of charging, the consumer can theoretically use any amount of energy up to that consumed by all the connected load at 100% use factor continuously at full load.

The unit energy cost decreases progressively with an increased energy usage since the total cost remains constant. The variations in total cost and unit cost are shown in Fig. 34.5 (*a*).

(2) Straight Line Meter Rate. This type of charging depends upon the amount of total energy consumed by the consumer. The bill is directly proportional to the energy consumed by the consumer and is represented by

$$z = b \cdot y$$

The drawback of this system, the consumer using no energy will not pay any amount although he has incurred some expenses to the power station. The second drawback is the rate of energy is fixed therefore this method of charging does not encourage the consumer to use more power. The variation of bill according to the variation of energy consumed is shown in Fig. 34.5 (*b*).

(3) Block-Metre Rate. The straight line metre rate charges the same unit price for all magnitudes of energy consumption. The increased generation (or consumption) spreads the item of fixed charge over a greater number of units of energy and, therefore, the price of energy should decrease with an increase in consumption. To overcome this difficulty, the block metre rate is used. In this method, the charging energy is done as stated below :

$$z_1 = b_1 y_2 + b_2 y_2 + b_3 y_3 + \dots$$

where $b_3 < b_2 < b_1$ and $y_1 + y_2 + y_3 + \dots = y$ (total energy consumption).

In gross meter rate system, the rate of unit charge decreases with increasing consumption of energy.

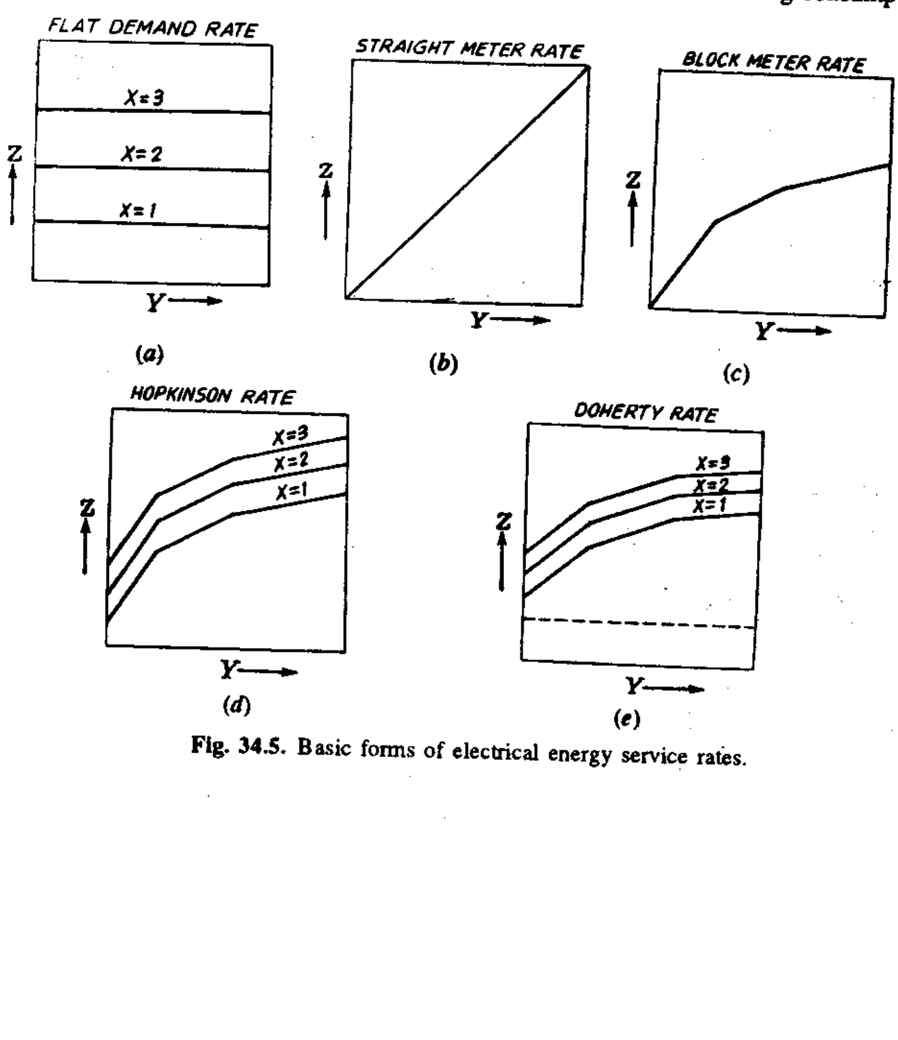


Fig. 34.5. Basic forms of electrical energy service rates.

The level of y_1, y_2, y_3 and so on is decided by the management to recover the capital cost of the plant. The variation of bill according to this method is shown in Fig. 34.5 (*c*).

(4) Hopkinson Demand Rate of Two-Part Tariff. This method of charging was proposed by Dr. John Hopkinson in 1892. This method charges the consumer according to his maximum demand and energy consumption. This can be expressed as

$$z = a + by.$$

This method requires two metres to record the maximum demand and the energy consumption of the consumer. This method is generally used for industrial customers. The variation of z with respect to y taking x as parameter is shown in Fig. 34.5 (*d*).

(5) Doherty Rate or Three Part Tariff. This rate of charging was suggested by Henry L. Doherty at the beginning of the twentieth century. According to this method of charging, the customer has to pay some fixed amount in addition to the charges for maximum demand and energy consumed. The fixed amount to be charged depends upon the occasional increase in prices and wage charges of the workers and so on. This is expressed as

$$x = ax + by + c$$

The Doherty rate is sometimes modified by specifying the minimum demand and minimum energy consumption that must be paid for. They are less than the minimum values specified.

When the generating capacity is less than the actual demand, then the customers are discouraged to use more power. Upto the certain power consumption, the charging rate is fixed (say Rs. 1.5/kW-hr upto 50 kW-hr units and if it exceeds than this, the charge is rapidly increased as Rs. 2.5/kW-hr. This is unfortunate but very common in India.

SOLVED PROBLEMS

Problem 34.1. *The cost of water softener plant used is 1,20,000 Rupees when newly installed. The life of the plant is considered as 12 years. The salvage value of the plant will be 8% of its cost when newly installed. The repair, maintenance and labour costs of the plant per year are 8000 rupees. The cost of chemical used per year is 5000 Rupees. Taking interest on sinking fund as 8%, find the annual cost of the plant.*

Solution. The following data is given

$P =$ Rs. 1,20,000, $S = \frac{8}{100} \times 1,20,000 = 9600$ Rupees

$r = 8\% = 0.08 \quad n = 12$

Annual sinking fund payment for the plant.

$$A = (P - S)\left[\frac{r}{(1+r)^n - 1}\right] = (1,20,000 - 9600)\left[\frac{0.08}{(1+0.08)^{12} - 1}\right]$$

$$= 110400\left[\frac{0.08}{2.52 - 1}\right] = 110400 \times \frac{0.08}{1.52} = 5820.$$

∴ Annual cost of the plant is given by

= Annual sinking fund payment + repair, maintenance and labour costs + chemical cost

= 5820 + 8000 + 5000 = **18820** **Rupees.**

Problem 34.2. *The cost of a small preheater is Rs. 12000 and its expected life is 16 years. The net annual instalment to recover the cost of equipment is Rs. 425. The interest is 5%. Using sinking fund method find the salvage value of the preheater after 16 years of service.*

Solution. $P =$ Rs. 12,000, $S = ?$, $r = 5\%$, $n = 16$, $A = 425$

The annual sinking fund payment for the plant is given by

$$A = (P-S)\left[\frac{r}{(1+r)^n - 1)}\right]$$

$$\therefore \quad 425 = (P-S)\left[\frac{5}{100} \times \frac{1}{(1+0.05)^{16}-1}\right] = (P-S)\left[\frac{0.05}{2.185-1}\right] = (P-S) \times \frac{0.05}{1.185}$$

$$\therefore \quad (P-S) = \frac{425}{1} \times \frac{1.185}{0.05} = 10060$$

$$\therefore \quad S = 12000 - 10060 = \mathbf{1940\ Rupees.}$$

Problem 34.3. *A small plant capital cost is Rs. 40,000 and its salvage value is Rs. 4000 at the end of a useful life of 20 years. Find its value half way through its life based on*

(a) straight line depreciation method (b) reducing balance depreciation method and (c) sinking fund depreciation at 6% compounded annually.

Solution. (*a*) In straight line method,

Total depreciation in 20 years

$= 40,000 - 4000 = \text{Rs. } 36000$

$\therefore$ Depreciation in 10 years = 36000/2 = Rs. 18000.

Plant value at the end of 10 years

$= 40,000 - 18,000 = $ **Rs. 22,000**

(*b*) In the **reducing balance depreciation** method, annual depreciation is taken as p % of the plant value at the beginning of that year.

Value at the end of n years is given by

$$V = C\,(1-p)^n$$

where C is capital value, p is annual depreciation as percentage and n is useful life

$$V_1 = 40,000\,(1-p)^{20} = 4000$$

$$\therefore \quad (1-p)^{20} = 0.1 \text{ or } (1-p) = (0.1)^{0.05}$$

Similarly, value V_2 at the end of 10 years

$$V_2 = 40,000\,(1-p)^{10} = 40,000\,[(0.1)^{0.05}]^{10} = 40,000\,(0.1)^{0.5}$$

$$= 40,000 \times 0.316 = 12.65 \times 1000 = \mathbf{Rs.\ 12650}$$

(*c*) The object of sinking fund method is to provide a sufficient amount at the end of useful life of the existing plant to replace it by a new one.

Let the initial capital cost is C, useful life is n years and its scrap value is C' at the end of n years.

$\therefore$ Q (replacement cost) $= C - C'$

where C' may be zero or positive depending upon the type of the plant.

In this case Q is given by

$$Q = \frac{q\,[(1+r)^n - 1]}{r}$$

where q is the amount set aside per year and r is an interest rate on the amount set aside (q) and n is the plant life.

As per given data

$$Q = 40,000 - 4000 = 36000$$

$$n = 20 \text{ and } r = 6\% = 0.06$$

$$\therefore \quad 36000 = \frac{q\,[(1+0.06)^{20} - 1]}{0.06} = 36.77\,q$$

$$\therefore \quad q = \frac{36000}{36.77} = \mathbf{978.8}$$

As the end of 10 years, the amount deposited in sinking fund

$$= \frac{978.8\ [(1 + 0.06)^{10} - 1]}{0.06} = \textbf{Rs. 12904}$$

∴ Value of the plant at the end of 10 years
$= 40{,}000 - 12904 = \textbf{Rs. 27096.}$

Problem 34.4. *A 30 MW plant has an overall η = 25%. The CV of fuel used is 25000 kJ/kg. Estimate the cost of coal per 24-hours if the load factor of the plant is 0.4. 1 tonne of coal costs Rs. 650.*

Solution. Energy generated in the form of electricity per day

$= \text{Plant capacity} \times \text{Load factor} \times 24$
$= 30 \times 0.4 \times 24$
$= 30 \times 9.6 = 288\ \text{MW} = \mathbf{288 \times 10^3\ kWh}$

Overall $\eta = \frac{\text{Energy generated}}{\text{Input}}$

Input energy/day $= \frac{288 \times 10^3}{0.25} = \mathbf{4 \times 288 \times 10^3\ kWh}$

$= 4 \times 288 \times 10^3 \times 3600\ \text{kJ}$

If m is the mass of fuel consumed per day

then $m \times 25000 = 4 \times 288 \times 10^3 \times 3600$

$$m = \frac{4 \times 288 \times 3600}{25}\ \text{kg/day}$$

$$= \frac{4 \times 288 \times 3600}{25 \times 1000}\ \text{tons/day}$$

$= 166$ tonnes/day

Cost of coal/day $= 166 \times 650 = \textbf{Rs. 107900.}$

Problem 34.5. *The energy consumption of a consumer per month is 2300 kW-hr. The maximum demand is 12 kW. Using the Hopkinson demand rate as given below, find : (a) Monthly bill of the consumer and unit energy cost, (b) Lowest possible bill for a month of 30 days and unit energy cost for the given energy consumption.*

The Hopkinson charges are as follows :

Demand Rates

0—5 kW = Rs. 200/kW
6—10 kW = Rs. 150/kW
11—15 kW = Rs. 120/kW

Energy Rates

First—100 kW-hr = Rs. 2 kW-hr
Next—500 kW-hr = Rs. 1.5 kW-hr
Next—2000 kW-hr = Rs. 1 kW-hr.
Excess over 2000 kW-hr = Rs. 0.8/kW-hr.

Solution. (*a*), Demand charges per month

$= 5 \times 200 + 5 \times 150 + 2 \times 120 = 1000 + 750 + 240 = \textbf{Rs. 1990.}$

Energy charge $= [100 \times 2 + 500 \times 1.5 + 1700 \times 1] = \text{Rs. } 2650.$

∴ Monthly bill $= 1990 + 2650 =$ **Rs. 4640.**

Average unit energy cost $= \frac{4640}{2300} =$ **Rs. 2.06/kWh**

(*b*) The lowest bill occurs when the demand is maximum which is only possible at 100% load.

∴ Maximum load = Average load $= \frac{2300}{30 \times 24} = 3.2$ kW.

∴ Demand charges $= 3.2 \times 200 =$ Rs. 640

Energy charges will be same = Rs. 2650

∴ Minimum monthly bill $= 640 + 2650 =$ Rs. 3290

Unit energy charge for this condition $= \frac{3290}{2300} =$ **Rs. 1.43/kWh.**

Problem 34.6. *The input-output curve of a 25 MW capacity generating power plant is given by*

$$I = 5 \times 10^6 (7 + 0.2 L + 0.1 \cdot L^2)$$

where I is in kJ/hr and L is in MW.

Find the average rate of heat supplied (heat supplied per MW-hr) when the plant is operating at 25 MW load for 10 hours in a day and it was kept hot at zero load for the remaining period of 14 hours. (b) Also find the saving in the heat rate if the same energy is produced for the whole day at constant load.

Solution. The input per hour at zero load ($L = 0$) is given by

$$I = 5 \times 10^6 (7 + 0 + 0) = 7 \times 5 \times 10^6 \text{ kJ/hr}$$

The input per hour at 25 MW load ($L = 25$) is given by

$$I = 5 \times 10^6 (7 + 0.2 \times 25 + 0.1 \times 625) = 74.5 \times 5 \times 10^6 \text{ kJ/hr.}$$

Total energy generated within 24 hours

$$= 25 \times 10 + 0 \times 14 = 250 \text{ MW-hrs}$$

Total energy input to the plant within 24 hours

$$= 74.5 \times 5 \times 10^6 \times 10 + 7 \times 5 \times 10^6 \times 14 = 843 \times 5 \times 10^6 \text{ kJ}$$

Average rate of heat input

$$= \frac{\text{Total heat supplied}}{\text{Total energy generated}} = \frac{843 \times 5 \times 10^6}{250} = \mathbf{3.38 \times 5 \times 10^6 \text{ kJ/MW-hr.}}$$

(*b*) If the same energy (250 MW-hrs) is generated within 24 hours, then the average load on the plant

$$= \frac{250}{24} = 10.41 \text{ MW}$$

The input per hour at $L = 10.41$ is given by

$$I = 5 \times 10^6 (7 + 0.2 \times 10.41 + 0.1 \times 10.41^2) = 19.95 \times 5 \times 10^6 \text{ kJ/hr.}$$

The heat rate at this load is given by

$$HR = \frac{I}{L} = \frac{19.95 \times 5 \times 10^6}{10.41} = \mathbf{1.915 \times 5 \times 10^6 \text{ kJ/MW-hr.}}$$

∴ Saving in heat rate $= 3.380 \times 5 \times 10^6 - 1.915 \times 5 \times 10^6 =$ **$1.465 \times 5 \times 10^6$ kJ/MW-hr.**

Problem 34.7. *An input-output curve of a 10 MW thermal station is given by an equation*

$$I = 5 \times 10^6 (18 + 12 L + 0.5 L^2) \text{ kJ/hr.}$$

where I is in kJ per hour and L is the load on power plant in MW.

Find (a) the load at which the efficiency of the plant will be maximum and (b) the increase in input required to increase the station output from 5 MW to 7 MW by using the input-output equation and by incremental rate curve.

Solution. (*a*) I (input) $= 5 \times 10^6 \, (18 + 12L + 0.5L^2)$ kJ/hr

L (output) = kJ/hr.

$$\eta \text{ (efficiency)} = \frac{L}{I} = \frac{1}{5 \times 10^6 \left(\frac{18}{L} + 12 + 0.5\,L \right)}$$

The efficiency will be maximum when $\left(\frac{18}{L} + 12 + 0.5L \right)$ will be minimum.

$$\therefore \quad \frac{d}{dL}\left(\frac{18}{L} + 12 + 0.5L \right) = 0$$

$$-\frac{18}{L_2} + 0.5 = 0$$

$$\frac{18}{L^2} = \frac{1}{2}$$

$\therefore$ $L = 6$ MW $= 6000$ kW $= 6000 \times 3600$ kJ/hr $=$ **216 × 10⁵ kJ/hr**

when $L = 6$ MW

$I = 5 \times 10^6 \, (18 + 12 \times 6 + 0.5 \times 36) = 5 \times 108 \times 10^6$ kJ/hr

$$\therefore \quad \eta_{max} = \frac{21.6 \times 10^6}{5 \times 108 \times 10^6} = \mathbf{0.04 = 4\%}$$

(*b*) I_5 (when $L = 5$) $= 5 \times 10^6 \, (18 + 12 \times 5 + 0.5 \times 25) = 5 \times 90.5 \times 10^6$ kJ/hr

I_7 (when $L = 7$) $= 5 \times 10^6 \, (18 + 12 \times 7 + 9.5 \times 49) = 5 \times 126.5 \times 16^6$ kJ/hr

$\therefore$ dI (increase in output to the plant per hour)

$= I_7 - I_5 = (126.5 - 90.5) \times 5 \times 10^6 =$ **$5 \times 36 \times 10^6$ kJ/hr**

If the increase is to be calculated by using incremental rate curve, then

IR (increase in input with unit increase in output) $= \frac{dI}{dL} = 5 \times 10^6 \, (12 + L)$

If the increase in input with increase in output for the given increase of output from 5 to 7 MW is considered a straight line, then

$$L = \frac{7 + 5}{2} = 6 \text{ MW}$$

$\therefore$ $IR = 5 \times 10^6 \, (12 + 6) = 18 \times 5 \times 10^6$ kJ/hr

$\therefore$ Total increase in input $= (18 \times 5 \times 10^6)\,(7 - 5) = 5 \times$ **36×10^6 kJ/hr.**

This shows that the increase in input required to increase the required output in both cases is same. This indicates that the incremental rate curve can be taken as straight line for small increase in output.

Problem 34.8. *To serve the load having the annual duration characteristics given in the following table :*

Load in kW	5,000	4,000	2,000	1,000	500
No. of Hours at Load	200	4,000	2,000	1,000	1,560

Two plants, a steam plant and diesel plant, are being considered. The coal of 28000 kJ/kg calorific value is available at Rs. 350 per ton and diesel oil of 36000 kJ/kg calorific value is available at Rs. 1200 per tonne.

The performance characteristics of the plants are given below :

Steam $I = 5 \times 10^6 \, (1.5 + 2L + 0.025\,L^3)$ kJ/hr

Diesel $I = 5 \times 10^6 \, (2.25 + L + 0.12\,L^2 - 0.004\,L^3)$ kJ/hr *where L is MW and I is in kJ per hour.*

The extra annual salary for steam plant compared to diesel plant is Rs. 320000 as number of operators required is more.

The capital investment cost for steam plant is Rs. 18500/kW and for diesel plant is Rs. 17000/kW. The fixed charge rate is 12% for each plant. Which plant should be selected for the required duty ?

Solution. The cost of coal energy per 10^6 kJ

$$= \frac{10^6}{28000 \times 1000} \times 350 = \text{Rs. } 12.5$$

The cost of diesel oil energy per 10^6 kJ

$$= \frac{10^6}{36000 \times 1000} \times 1200 = \text{Rs. } 33.3$$

The total energy required per year can be calculated by using the given input equations for both plants.
Say input to steam plant at 5 MW output

$I = 5 \times 10^6 (1.5 + 2 \times 5 + 0.025 \times 125) = 73.125 \times 10^6$ kJ/hr

Similarly, we can find out the inputs at different loads for both plants and are tabulated in the table below :

Steam Plant

$$\text{Fixed cost} = \text{capital cost} \times \frac{12}{100} = 5000 \times 18500 \times \frac{12}{100} = \text{Rs. } 11100 \times 10^3/\text{year}$$

Load in MW (L)	*No. of hours at load*	*MW-hrs*	*Steam plant*		*Diesel plant*	
			Input rate in 10^6 kJ per hour	*Total input in 10^9 kJ*	*Input rate in 10^6 kJ per hour*	*Total input in 10^9 kJ*
a	*b*	*c*	*d*	$e = b \times d$	*f*	$g = b \times f$
5	200	1000	73.125	14.625	53.75	10.75
4	4000	16000	55.5	222	42.125	168.5
2	2000	4000	28.5	57	23.8	47.6
1	1000	1000	17.625	17.625	16.85	16.85
0.5	1560	780	12.5	19.5	13.9	21.68
Total	8760	22780	—	330.75	—	265.38
Average heat rate in kJ per kW-hr			—	$\frac{330.75 \times 10^9}{22780 \times 1000}$ = 14520	—	$\frac{265.38 \times 10^9}{22780 \times 1000}$ = 11650

Operating cost $= \text{Fuel cost} + \text{extra salaries} = \frac{330.75 \times 10^9}{10^6} \times 12.5 + 320000$

$= 4134 \times 10^3 + 320 \times 10^3 = \text{Rs. } 4454 \times 10^3/\text{year}$

Total cost = Fixed cost + Operating cost

$= 11100 \times 10^3 + 4454 \times 10^3 =$ **Rs. 15554 × 10³**

Diesel Plant

$$\text{Fixed cost} = \text{Capital cost} \times \frac{12}{100} = 5000 \times 17000 \times \frac{12}{100} = \text{Rs. } 10200 \times 10^3/\text{year}$$

Operating cost = Fuel cost only

$$= \frac{265.38 \times 10^9}{10^6} \times 33.3 = \text{Rs. } 8837 \times 10^3/\text{year}$$

Total cost $= 10200 \times 10^3 + 8837 \times 10^3 =$ **Rs. 19037 × 10³.**

The steam plant would be the choice under the given circumstances despite the higher investment and the greater relative labour cost. These items are outweighed by the cheaper fuel cost.

Problem 34.9. *The input-output curve of a 60 MW power station is given by*

$$I = 5 \times 10^6 \, [8 + 8L + 0.4L^2] \text{ kJ/hr}$$

where I is the input in kJ/hr and L is load in MW :

(a) Determine the heat input per day to the power station if it works for 20 hours at full load and remaining period at no load.

(b) Also find the saving per kWh of energy produced if the plant works at full load for all 24 hours generating the same amount of energy.

Solution. Total energy generated by the power plant during 24 hours

$$= 20 \times 60 + 4 \times 0 = 1200 \text{ MWh}$$

Input to the plant when the plant is running at full load.

$I_{60} = 5 \times 10^6 \, [8 + 8 \times 60 + 0.4 \times 60^2] \times 20 = 5 \times 10^6 \times 20 \, [8 + 480 + 1440]$

$= 1928 \times 20 \times 5 \times 10^6$ kJ during 20 hours when the plant was running at full load

Input at no load $I_0 = 5 \times 10^6 \, [8] \times 4$

$= 32 \times 5 \times 10^6$ kJ during 4 hours when the plant was running at no load.

Total input to the plant during 24 hours $= I_{60} + I_0$

$= 1928 \times 20 \times 5 \times 10^6 + 32 \times 5 \times 10^6 = 5 \times 10^6 \, [38560 + 32]$

$= 38592 \times 5 \times 10^6$ kJ/day.

$$\text{Average heat supplied per kWh generated} = \frac{38592 \times 5 \times 10^6}{1200 \times 10^3} = 32 \times 5 \times 10^3 \text{ kJ/kWh}$$

If the same energy is generated within 24 hours, the average load is given by

$$\text{Average load} = \frac{1200}{24} = 50 \text{ MW}.$$

Heat supplied during 24 hours in this case

$I_{50} = 5 \times 10^6 \, [8 + 8 \times 50 + 0.4 \times 50^2] \times 24 = 5 \times 10^6 \, [8 + 400 + 1000] \times 24$

$= 5 \times 10^6 \times 24 \times 1408$ kJ/day $=$ **33792 × 5 × 10⁶ kJ/day**

Net saving per day $= 38592 \times 5 \times 10^6 - 33792 \times 5 \times 10^6 = 4800 \times 5 \times 10^6$ kJ/day

$$\therefore \text{ Saving per kWh} = \frac{4800 \times 10^6}{1200 \times 10^3} = \mathbf{4 \times 10^3 \text{ kJ/kWh}}.$$

Problem 34.10. *The incremental fuel costs for two generating units A and B of a power plant are given by the following equations :*

$$\frac{dF_a}{dP_a} = 0.065 \, P_a + 25$$

$$\frac{dF_b}{dP_b} = 0.08 \, P_b + 20$$

where F is fuel cost in rupees per hour and P is power output in MW. Find : (a) the economic loading of the two units when the total load supplied by the power plants is 160 MW. (b) The loss in fuel cost per hour if the load is equally shared by both units.

Solution. (*a*) The given data is

$$P_a + P_b = 160 \quad \text{...(1)}$$

The condition required for economic loading

$$\frac{dF_a}{dP_a} = \frac{dF_b}{dP_b} \, .$$

$$\therefore \quad 0.065 \, P_a + 25 = 0.08 \, P_b + 20 \quad \text{...(2)}$$

Solving Eqns. (1) and (2), we get

$$P_a = \mathbf{53.5\ MW} \text{ and } P_b = \mathbf{106.5\ MW}$$

(*b*) If the load is equally shared by both the units (supplying 160/2 = 80 MW each), then the increase in cost of fuel for unit *A* is given by

$$= \int_{53.5}^{80} (0.065\ P_a + 25)\ dP_a = \left[\frac{0.065}{2} P_a^2 + 25\ P_a \right]_{53.5}^{80} = \text{Rs. } 765/\text{hr}$$

Increase in cost for unit *B*

$$= \int_{106.5}^{80} (0.08\ P_b + 20)\ dP_b = -\left[\frac{0.08}{2} P_b^2 + 20\ P_b \right]_{80}^{106.5} = \text{Rs. } -730/\text{hr}$$

This indicates that the cost of fuel for unit *B* decreases.

Net increase in cost due to departure form economic distribution of load

$$= 765 - 730 = \textbf{Rs. 35/hr.}$$

Problem 34.11. *Two steam turbines each of 20 MW capacity take a total load of 30 MW. The steam consumption rates in kg per hour for both turbines are given by the following equations :*

$S_1 = 2000 + 10\ L_1 - 0.0001\ L_1^2$

$S_2 = 1000 + 7\ L_2 - 0.00005\ L_2^2$

L represents the load in kW and S represents the steam consumption per hour.

Find the most economical loading when the total load taken by both units is 30 MW.

Solution. $L_1 + L_2 = 30000$ ...(1)

For the most economical loading, the required condition is

$$\frac{dS_1}{dL_1} = \frac{dS_2}{dL_2}$$

$\therefore \quad 10 - 0.0002\ L_1 = 7 - 0.0001\ L_2$ ...(2)

Solving Equations (1) and (2), we get

L_1 = 20,000 kW = 20 MW and L_2 = 10000 kW = 10 MW.

Problem 34.12. *Two electrical units used for same purpose compared for their economical working :*

(a) Cost of first unit is Rs. 5000 and it takes 100 kW.

(b) Cost of second unit is Rs. 14000 and it takes 60 kW.

Each of them has a useful life of 40,000 hours. Which unit will prove economical if the energy is charged at Rs. 80 per kW of maximum demand per year and 5 P. per kW-hr ? Assume both units run at full load.

Solution. (*a*) *First Unit*

Capital cost of unit per hour $= \frac{5000}{40000}$ = Re. 0.125

Maximum demand = 100 kW

Charge for maximum demand per hour $= \frac{100 \times 80}{8760}$ = Rs. 0.914

Energy charge per hour = Maximum demand × one hour × charge per kW hr

$$= 100 \times 1 \times \frac{5}{100} = \text{Rs. } 5.$$

∴ Total charges per hour for the operation of first unit

$$= 0.125 + 0.914 + 5.0 = \textbf{Rs. 6.039.}$$

(*b*) *Second Unit*

Capital cost of unit per hour $= \frac{14000}{40000}$ = Re. 0.35

Charge for maximum demand per hour = $\frac{60 \times 80}{8760}$ = Re. 0.548.

Energy charge per hour = $(60 \times 1) \times \frac{5}{100}$ = Rs. 3

Total charges per hour for the operation of second unit

$= 0.35 + 0.548 + 3.0 = \mathbf{3.898}.$

The charges of operation for the second unit per hour are less than the charges of operation for the first unit, therefore the second unit is more economical in this case.

Problem 34.13. *A new industry requires a maximum demand of 800 kW at 30% load factor. The following two power suppliers are available :*

(a) Public supply charges Rs. 500/kW of maximum demand and 40 P./kW-hr. The capital cost is 8 × 10^5 rupees and interest and depreciation charges on capital are 10%.

(b) A private oil engine station requires Rs. 3 × 10^6 capital. The interest and depreciation on the capital are 12%. The maintenance and labour charges are 10 P. per kW-hr energy generated. The fuel consumption is 0.35 kg/kW-hr and cost of fuel is 80 P. per kg.

Find which supply will be more economical.

Solution. Average load = Maximum demand × Load factor = 800 × 0.3 = **240 kW**

Energy required per year = 240 × 8760 = 210.24 × 10^4 kW-hrs.

(*a*) *Public Supply*

Charges for maximum demand per year = 500 × 800 = 4,00,000 = 4 × 10^5

Interest and depreciation = $\frac{10}{100} \times 8 \times 10^5 = 80{,}000 = 0.8 \times 10^5$

Energy cost per year = $\frac{40}{100} \times 210.24 \times 10^4 = 841000 = 8.41 \times 10^5$

Total cost = $4 \times 10^5 \times 0.8 \times 10^5 + 8.41 \times 10^5 = 13.21 \times 10^5$

Average energy cost = $\frac{13.21 \times 10^5}{210.24 \times 10^4}$ = Rs. 0.63/kWh

(*b*) *Private Supply*

Fuel consumption per year = $\frac{0.35 \times 210.24 \times 10^4}{1000}$ = 735 tons

Cost of fuel = $735 \times 1000 \times \frac{80}{100}$ = Rs. 588000 = Rs. 5.88 × 10^5.

The maintenance and labour charges per year

$= \frac{10}{100} \times 210.24 \times 10^4$ = Rs. 210240 = Rs. 2.1024 × 10^5

Interest and depreciation = $\frac{12}{100} \times 3 \times 10^6$ = Rs. 3.6 × 10^5

Total cost = $5.88 \times 10^5 + 2.1024 \times 10^5 + 3.6 \times 10^5 = 11.5824 \times 10^5$

∴ Average energy cost = $\frac{11.5824 \times 10^5}{210.24 \times 10^4}$ = **Rs. 0.55/kW-hr.**

As the average energy cost for oil engine is less than the public supply, the oil engine generation is more preferable.

Problem 34.14. *A load having a maximum demand of 80 MW and a load factor of 40% may be supplied by one of the following schemes :*

(a) A steam station capable of supplying the whole load.

(b) A steam station in conjunction with pump-storage plant which is capable of supplying 120 × 10⁶ kW-hr energy per year with a maximum output of 30 MW.

Find out the cost of energy per unit in each of the two cases mentioned above.

Use the following data :

Capital cost of steam station = Rs. 18000/kW of installed capacity

Capital cost of pump storage plant = Rs. 12000/kW of installed capacity

Operating cost of steam plant = Rs. 0.80 kW-hr

Operating cost of pump storage plant = Rs. 0.05 kW-hr

Interest and depreciation together on the capital invested should be taken as 12%. Assume that no spare capacity is required.

Solution. (*a*) Capital cost of steam station

$= 80 \times 1000 \times 18000 = \text{Rs. } 144 \times 10^7$

Interest and depreciation $= \dfrac{12}{100} \times 144 \times 10^7 = \text{ Rs. } 12 \times 144 \times 10^5$

Average load = Max. demand × Load factor $= 80 \times 1000 \times 0.4 = 32 \times 10^3$ kW

Energy supplied per year = Average load × 8760 $= 32 \times 10^3 \times 8760$ kW-hrs.

∴ Interest and depreciation charges per unit of energy

$= \dfrac{12 \times 144 \times 10^5}{32 \times 10^3 \times 8760} \times 100 =$ **Rs. 0.616 = 61.6 paise/kWh**

∴ Total cost per unit = 80 + 61.6 = 141.6 paise per unit = **Rs. 1.416/kWh**

(*b*) When the energy is supplied by steam and pump storage plant,

The load supplied by the steam plant = 80 − 30 = 50 MW

∴ Capital cost of steam plant $= 50 \times 1000 \times 18000 = \text{Rs. } 90 \times 10^7$

Capital cost of pump storage plant $= 30 \times 1000 \times 12000 = \text{Rs. } 36 \times 10^7$

∴ Total capital cost of combined station $= 90 \times 10^7 + 36 \times 10^7 =$ **Rs. 126 × 10⁷**

Interest and depreciation charges on capital investment

$= \dfrac{12}{100} \times 126 \times 10^7 = \text{Rs. } 15.12 \times 10^7$

∴ Operating cost of pump storage plant

$= \dfrac{5}{100} \times 120 \times 10^7 = \text{Rs. } 0.6 \times 10^7$

The energy units supplied by steam station

= Total units required − energy units supplied by pump storage plant

$32 \times 8760 \times 10^3 - 120 \times 10^6 = 160.32 \times 10^6$ kW-hr.

Operating cost of the steam station $= \dfrac{80}{100} \times 160 \times 10^6 = \text{Rs. } 12.8 \times 10^7$

Total cost per year $= 15.12 \times 10^7 + 0.6 \times 10^7 + 12.8 \times 10^7 = \text{Rs. } 28.52 \times 10^7$

The cost per unit $= \dfrac{28.52 \times 10^7}{32 \times 10^3 \times 8760} =$ **Rs. 1.02 P./kW-hr.**

Repeat the above example with 75% load factor.

It will be obvious from the results that the cost of generation becomes less with higher load factor irrespective of the type of plant used for generation.

Problem 34.15. *Find the cost of generation per kW-hr from the following data :*

Capacity of the plant = 120 MW

Capital cost = Rs. 12000 per kW installed

Interest and depreciation = 10% on capital

Fuel consumption = 1.2 kg/kW-hr

Fuel cost = Rs. 400 per tonne

Salaries, wages, repairs and maintenance = 600,000 per year

The maximum demand is 80 MW and load factor is 40%.

Solution. Capital investment $= 120 \times 1000 \times 12000 = \text{Rs. } 144 \times 10^7$

Interest and depreciation $= \frac{10}{100} \times 144 \times 10^7 = \textbf{Rs. 14.4} \times \mathbf{10^7}$

Average load = Maximum demand × Load factor

$= 80 \times 0.4 = 32$ MW

Total energy generated $= 32 \times 1000 \times 8760$ kW-hr.

$= 280 \times 10^6$ kW-hr

Fuel consumption $= 1.2 \times 280 \times 10^6 = 336 \times 10^6$ kg

Fuel cost $= \frac{400}{1000} \times 336 \times 10^7 = \textbf{Rs. 13.44} \times \mathbf{10^7}$

Salaries, wages and repairs $= \text{Rs. } 0.6 \times 10^6 = \textbf{Rs. 0.06} \times \mathbf{10^7}$

Total annual charges $= 14.4 \times 10^7 + 13.44 \times 10^7 + 0.06 \times 10^7$

$= 27.9 \times 10^7$

∴ Cost of generation $= \frac{27.9 \times 10^7}{280 \times 10^7} = \textbf{Rs. 0.996 kWh.}$

Problem 34.16. *The following data for a 2200 kW diesel power station is given. The peak load on the plant is 1600 kW and its load factor is 45%.*

Capital cost / kW installed = Rs. 15000

Annual costs = 15% of capital

Annual operating costs = Rs. 60,0000

Annual maintenance costs = Fixed Rs. 10,0000 and Variable Rs. 20,0000

Cost of fuel = Rs. 0.8 per kg

Cost of lubricating oil = Rs. 40 per kg

C.V. of fuel = 40,000 kJ/kg

Consumption of fuel = 0.5 kg/kWh

Consumption of lubricant oil $= \frac{1}{400}$ *kg/kWh.*

Determine (a) the annual energy generated and (b) the cost of generation Rs./kWh.

Solution. Capital cost of the plant $= 2200 \times 15000 = \text{Rs. } 33 \times 10^6$/year

Interest on capital $= 33 \times 10^6 \times \frac{15}{100} = \text{Rs. } 4.95 \times 10^6$/year

Annual energy generated = Max. demand × L.F. × 8760

$= 1600 \times 0.45 \times 8760 = \mathbf{6.3 \times 10^6}$ **kWh/year**

Fuel consumption $= 0.5 \times 6.3 \times 10^6 = 3.15 \times 10^6$ kg/year

Cost of fuel $= 3.15 \times 10^6 \times 0.8 =$ Rs. 2.52×10^6 kg/year

Lubricant consumption $= \frac{1}{400} \times 6.3 \times 10^6 = 1.575 \times 10^4$ kg/year

Cost of lubricant oil $= 40 \times 1.575 \times 10^4 =$ Rs. 0.63×10^6/year

Total fixed cost = Interest + Maintenance (fixed)

$= 4.95 \times 10^6 + 0.1 \times 10^6 =$ **Rs. 5.05 × 10⁶ kg/year**

Total running or variable costs = fuel cost + lubricant cost + maintenance (running) + annual operating costs

$= 2.52 \times 10^6 + 0.63 \times 10^6 + 0.2 \times 10^6 + 0.6 \times 10^6$

$= (1260 + 19.7 + 20 + 60) \times 10^3 =$ **Rs. 3.95 × 10⁶/year.**

Total cost = Fixed cost + running cost

$= 5.05 \times 10^6 + 3.95 \times 10^6 =$ **Rs. 9 × 10⁶/year**

Generation cost $= \frac{9 \times 10^6}{6.3 \times 10^6} =$ **Rs. 1.43/kWh**

Problem 34.17. *The following data relates to a steam power station of 120 MW capacity which takes 100 MW peak demand at 80% load factor.*

Annual cost towards the interest and depreciation	*= Rs. 1000/kW installed*
Operating costs	*= Rs. 1200 × 10⁴/year*
Maintenance costs	*= Rs. 200 × 10⁴/year (fixed)*
	= Rs. 400 × 10⁴/year (variable)
Miscellaneous costs	*= Rs. 100 × 10⁴/year*
Cost of coal used	*= Rs. 320/ton*
C.V. of fuel used	*= 25000 kJ/kg*
Overall efficiency of the plant	*= 20%*
Steam consumption in kg/kWh	*= (0.8 + 3.5 × L.F.)*

Determine (a) Coal cost per year and (b) Overall cost of generation.

Solution. Energy generated = Max. load × L.F. × 8760

$= 100 \times 10^3 \times 0.8 \times 8760 = 701 \times 10^6$ kWh/year

Steam consumption per kW load $= 0.8 + 3.5 \times 0.8 = 3.6$ kg

1 kW load generates 0.8 kWh energy as load factor is 0.8

∴ Steam consumption per kWh

$$= \frac{3.6}{0.8} = \mathbf{4.5\ kg}$$

If W_c is the weight of coal in tons used per year, then we can write

$$W_c \times 10^3 \times 25000 \times \frac{20}{100} = (701 \times 10^6) \times 3600$$

$$\therefore \quad W_c = \frac{701 \times 10^6 \times 3600 \times 100}{10^3 \times 25000 \times 20} = \mathbf{504.7 \times 10^3\ tons/year}$$

∴ Cost of coal $= 504.7 \times 10^3 \times 320 =$ **Rs. 161.5 × 10⁶/year**

Total fixed costs $= 1000 \times 120 \times 10^3 + 200 \times 10^4 =$ Rs. 122×10^6/year

Total variable costs $= 1200 \times 10^4 + 400 \times 10^4 + 100 \times 10^4 + 161.5 \times 10^6$

$= (12 + 4 + 1 + 161.5) \times 10^6 = \text{Rs. } 178.5 \times 10^6$

$\therefore$ Total annual cost $= (122 + 178.5) \times 10^6 = \text{Rs. } 300.5 \times 10^6$

Generation cost $= \dfrac{300.5 \times 10^6}{701 \times 10^6} =$ **Rs. 0.43 /kWh.**

Problem 34.18. *A power system requires a maximum load of 80 MW at 35% L.F. It can be supplied by any of the following schemes :*

(a) A steam plant capable to supply the whole load.

(b) A steam plant with hydel plant where energy supplied by steam plant is 120×10^6 kWh/year with a maximum load of 50 MW.

Cost	*Steam plant*	*Hydro plant*
Capital cost	*Rs. 18000/kW installed*	*Rs. 30000/kW installed*
Operating cost	*Rs. 0.5/kWh*	*Rs. 0.1/kWh*
Transmission	*Negligible*	*Rs. 0.05/kWh*

Assume interest and depreciation at 12% of capital for steam plant and 10% of capital for hydro plant. Calculate the annual cost and cost/kWh for each plant.

(c) If the whole load is supplied by a Nuclear plant, determine annual cost. Take capital cost of Rs. 25000/kW and running cost of Rs. 0.25/kWh. Assume interest and depreciation as 10% per annum.

Solution. Energy required per year = Max. load × L.F. × 8760

$= 80 \times 10^3 \times 0.35 \times 8760 = 245 \times 10^6$ kWh.

(*a*) **Steam plant**

Interest and depreciation (fixed cost) $= \dfrac{12}{100} \times 80 \times 10^3 \times 1800 =$ **Rs. 17.28 × 10⁶/year**

Operating cost $= 0.5 \times 245 \times 10^6 =$ **122.5×10^6/year**

Total cost $= (17.28 + 122.5) \times 10^6 =$ **Rs. 139.78×10^6/year**

Overall cost per kWh $= \dfrac{139.78 \times 10^6}{245 \times 10^6} =$ **Rs. 0.57/kWh**

(b) (i) Hydel plant

Interest and depreciation (fixed cost) $= \dfrac{10}{100} \times (80 - 50) \times 10^3 \times 30{,}000 =$ **Rs. 90×10^6/year**

Energy supplied by the hydro plant $= (245 - 120) \times 10^6 =$ **125×10^6 kWh/year**

Operating or running cost including transmission $= 125 \times 10^6 \times 0.1 + 0.05 =$ **Rs. 18.75×10^6/year**

(*b*) **Steam station**

Load taken $= \dfrac{120 \times 10^6}{8760} = 13.7 \times 10^3$ kW

Max. load (Minimum plant capacity) $= \dfrac{13.7 \times 10^3}{0.35} =$ **39.15×10^3 kW**

Interest and depreciation $= \dfrac{12}{100} \times 39.15 \times 10^3 \times 18000 =$ **Rs. 84.56×10^6/year**

Operation cost = $120 \times 10^6 \times 0.5$ = Rs. 60×10^6/year

Total cost of both the plants

$$= 90 \times 10^6 + 18.75 \times 10^6 + 84.56 \times 10^6 + 60 \times 10^6$$

$$= \text{Rs. } 253.31 \times 10^6\text{/year}$$

$$\text{Overall cost per kWh} = \frac{253.31 \times 10^6}{245 \times 10^6} = \textbf{Rs. 1.034/kWh}$$

(c) Nuclear plant

$$\text{Interest and depreciation} = 80 \times 10^3 \times 25000 \times \frac{10}{100} = \text{Rs. } 200 \times 10^6\text{/year}$$

Running cost = $245 \times 10^6 \times 0.25$ = Rs. 61.25×10^6/year

Total cost = $(200 + 61.25) \times 10^6$ = Rs. 261.25×10^6/year

$$\text{Overall cost per kWh} = \frac{261.25 \times 10^6}{245 \times 10^6} = \textbf{Rs. 1.07/kWh.}$$

Problem 34.19. *A factory wants 900 kW load at 30% load factor. The following two alternatives are available to the factory owner :*

(i) **A private diesel generating plant**

Capital cost	*= Rs. 90 × 10⁵*
Fuel cost	*= Rs. 800/ton*
Fuel consumption	*= 0.3 kg/kWh-generated*
Cost of maintenance	*= 2.5 paise/kWh-generated*
Cost of lubricating oil, water, store etc.	*= 0.3 paise/kWh-generated*
Wages	*= Rs. 180000/year*
Interest and depreciation	*= 10% per year.*

(ii) **Public supply**

Rs. 1500/kW of max. demand per year and 80 paise/kWh. Which will be more economical to the factory owner ?

Solution. The supply will be more economical whose yearly costs are less.

(i) Private plant

Interest and depreciation $= \frac{10}{100} \times 90 \times 10^5 =$ **Rs. 9 × 10⁵/year**

Number of units of energy required per year

$= 900 \times 0.3 \times 8760 = 270 \times 8760$ kWh/year

Fuel required $= 0.3 \times 270 \times 8760 = 81 \times 8760$ kg/year

Fuel cost $= 81 \times 8760 \times \frac{80}{100} =$ **Rs. 5.68 × 10⁵/year.**

Cost of maintenance, oil and water

$= \frac{(3 + 2.5)}{100} \times 270 \times 8760 =$ **Rs. 13 × 10⁵/year**

Wages = **Rs. 1.8 × 10⁵/year**

Total cost of the plant per year

$= 9 \times 10^5 + 5.68 \times 10^5 + 18 \times 10^5 =$ **Rs. 45.68 × 10⁵**

The energy cost $= \frac{45.68 \times 10^5}{270 \times 8760} \times 100 =$ **Rs. 1.93/kWh**

(ii) Public Supply

Total cost $= 1500 \times 900 + \frac{80}{100} \times 270 \times 8760$

$= (135 + 189.3) \times 10^4 =$ **Rs.** 324.2×10^4/year

Energy cost $= \frac{324.2 \times 10^4}{270 \times 86760} =$ **Rs. 1.37/kWh**

The public supply set is preferable as its cost is less than diesel set.

Problem 34.20. *The following data pertains to a power plant of 120 MW capacity :*

The capital cost	*= Rs. 15000/kW*
Interest and depreciation	*= 10% on capital*
Annual running charges	*= Rs.* 20×10^6
Profit to be gained	*= 10% of the capital*
The energy consumed by the power plant auxiliaries	*= 5% of generated*
The annual load factor	*= 0.6*
Annual capacity factor	*= 0.5*

Calculate (a) the reserve capacity and (b) cost of generation per kWh.

Solution.

$$\text{Load Factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

$$\text{Capacity factor} = \frac{\text{Average load}}{\text{Plant capacity}}$$

$$\therefore \quad \frac{\text{Load factor}}{\text{Capacity factor}} = \frac{\text{Plant capacity}}{\text{Maximum demand}}$$

$$\therefore \quad \frac{0.6}{0.5} = \frac{120}{\text{Maximum demand}}$$

$$\therefore \quad \text{Maximum demand} = \frac{120 \times 0.5}{0.6} = 100 \text{ MW}$$

$$\therefore \quad \text{Reserve capacity} = \text{Plant capacity} - \text{Maximum demand}$$

$= 120 - 100 =$ **20 MW**

Average load = Load factor × Maximum demand

$= 0.6 \times 120 = 72$ MW $=$ **72×10^3 kW**

Energy produced/year = Average load × 8760

$= 72 \times 10^3 \times 8760 =$ **631×10^6 kWh.**

As 5% of the total energy generated is used for the auxiliaries, only 95% of the energy is sold.

∴ Energy available for sale $= 631 \times 0.95 \times 10^6 = 600 \times 10^6$ kWh

Total capital cost of the plant $= 15000 \times 120 \times 10^3 =$ Rs. 180×10^7

Interest and depreciation $= \frac{1}{10} \times 180 \times 10^7 =$ Rs. 18×10^7

Profit on the capital $= \frac{1}{10} \times 180 \times 10^7 = \text{Rs. } 18 \times 10^7$

Annual running charges $= \text{Rs. } 20 \times 10^6 = \text{Rs. } 2.0 \times 10^7$

$\therefore$ Total charges to be recovered by selling the energy generated

$= 18 \times 10^7 + 18 \times 10^7 + 0.2 \times 10^7$

$= \textbf{Rs. } \mathbf{38 \times 10^7}$

$\therefore$ Cost of energy generated $= \frac{38 \times 10^7}{600 \times 10^6} =$ **Rs. 0.65/kWh**

Problem 34.21. *From the following data, estimate the generating cost in paise/kWh-delivered by the station :*

Installed capacity of the plant = *142.5 MW*
Annual load factor = *60%*
Capacity factor = *50%*
Capital cost of the plant = *Rs. 130* $\times 10^7$
Annual cost of coal, oil tax and salaries = *Rs. 18.8* $\times 10^7$
Rate of interest = *5% of capital*
Rate of depreciation = *5% of capital*
Units of energy used to run the plant auxiliary = 6% of the total unit supplied
What is the reserve available ?

Solution. $\frac{\text{C.F.}}{\text{L.F.}} = \frac{\text{Max. demand}}{\text{Plant capacity}}$

$\therefore \quad \frac{0.5}{0.6} = \frac{MW_{max}}{142.5}$

$\therefore \quad MW_{max} = 142.5 \times \frac{0.5}{0.6} = \mathbf{118.75\ MW}$

Reserve capacity $= \text{Plant capacity} - MW_{max}$

$= 142.5 - 118.75 = \mathbf{23.75\ MW}$

Yearly energy supplied by the plant

$= MW_{max} \times \text{L.F.} \times 8760$

$= 118.75 \times 10^3 \times 0.6 \times 8760$

$= 616.5 \times 10^6$ kWh

Yearly energy generated $= \left(1 + \frac{6}{100}\right) \times 616.5 \times 10^6$

$= \mathbf{653.43 \times 10^6\ kWh}$

Interest and depreciation

$= \left(\frac{5+5}{100}\right) \times 130 \times 10^7 = \textbf{Rs. } \mathbf{13 \times 10^7/year}$

Running cost $= \text{Rs. } 18.8 \times 10^7\text{/year}$

Total cost $= (1.3 + 18.8) \times 10^7 = \textbf{Rs. } \mathbf{31.8 \times 10^7/year}$

Overall cost of generation $= \frac{31.8 \times 10^7}{653.43 \times 10^6} \times 100 =$ **Rs. 0.487/kWh.**

Problem 34.22. *The energy is supplied to a group of 50,000 domestic consumers. The revenues expected per year from the consumers are given below :*

Fixed charges = Rs. 2.5 × 10^7, Energy charges = Rs. 2 × 10^7, Customer charges = Rs. 0.5 × 10^7

Profit = Rs. 20 × 10^5, Maximum demand = 5000 kW, Diversity factor = 4, Load factor = 0.3

Form a three charge rate allowing 25% profit in fixed charges, 50% in energy charges and remaining 25% in customer charges.

Solution.

$$\text{Fixed cost} = 2.5 \times 10^7 + \frac{25}{100} \times 20 \times 10^5 = \text{Rs. } 255 \times 10^5$$

$$\text{Energy charges} = 2 \times 10^7 + \frac{50}{100} \times 20 \times 10^5 = \text{Rs. } 210 \times 10^5$$

$$\text{Customer charges} = 0.5 \times 10^7 + \frac{25}{100} \times 20 \times 10^5 = \text{Rs. } 55 \times 10^5$$

Sum of individual maximum demands of customers

= Max. demand × Diversity factor

= $5000 \times 4 = 2 \times 10^4$ kW

Energy used per year

= Average load × 8760

= Max. demand × Load factor × 8760

= $5000 \times 0.3 \times 8760 = 13.14 \times 10^6$ kW-hrs.

$$\therefore \text{ Fixed cost per kW per year} = \frac{255 \times 10^5}{2 \times 10^4} = \textbf{Rs. 127.5/kW}$$

$$\text{Charges per customer per year} = \frac{55 \times 10^5}{50{,}000} = \text{Rs. } 110$$

$$\text{Energy rate} = \frac{210 \times 10^5}{13.14 \times 10^6} = \textbf{Rs. 1.6/kWh.}$$

Problem 34.23. *The capital cost of a hydro-power station of 100 MW capacity is Rs. 10,000/kW. The annual depreciation charges are 15% of the capital cost. A royalty of Rs. 2/kW per year and Rs. 0.3/kWh generated is to be paid for using the river water for power generation. The maximum demand on power station is 70 MW and annual load factor is 0.6. The annual salaries, maintenance charges are Rs. 10^7. If 20% of this expense is also chargeable as fixed charges, calculate the generation charge in two-part-tariff.*

Solution. The number of units generated per year

= $(70 \times 10^3) \times 0.6 \times 8760 = \mathbf{367.4 \times 10^6}$ **kWh**

Capital cost of the plant

= $100 \times 10^3 \times 10^4 =$ **Rs.** $\mathbf{100 \times 10^7}$

Annual fixed charges

$$\text{Depreciation} = \frac{15}{100} \times 100 \times 10^7 = \textbf{Rs. } \mathbf{15 \times 10^7}$$

$$\text{Salaries and maintenance} = \frac{20}{100} \times 10^7 = \text{Rs. } 0.2 \times 10^7$$

Total annual fixed charges = $150 \times 10^6 + 0.2 \times 10^7 = 152 \times 10^6$

Cost per kW = Cost due to fixed charges + Royalty

$$= \frac{152 \times 10^6}{70 \times 10^3} + 2 = \textbf{Rs. 2171/kW}$$

Annual running charges

Salaries and maintenance = 0.8×10^6 = **Rs. 0.8 × 10⁶**

Total cost = Cost due to running charges + Royalty

$$= \frac{0.8 \times 10^7}{367.9 \times 10^6} + 0.3 = 0.022 + 0.3 = 0.322 = \textbf{32.2 paise/kWh}$$

Two part traiff = **Rs. (2171/kW + 0.322/kWh)**

Problem 34.24. *The annual costs of operating a 25-MW thermal plant are given below :*

Capital cost of plant	*= Rs. 12000/kW*
Interest + insurance + depreciation	*= 10% of plant cost*
Capital cost of primary and secondary distribution	*= Rs. 15 × 10⁶*
Interest + insurance + depreciation on the capital cost of primary and secondary distribution	*= 5% of capital cost*
Plant maintenance cost	*= Rs. 80 × 10⁴ per year*
Maintenance cost of primary and secondary equipments	*= Rs. 2 × 10⁶/year*
Salaries and wages	*= Rs. 6 × 10⁶ per year*
Consumption of coal	*= 80 × 10³ tonnes per year*
Cost of Coal	*= Rs. 800 per tonne*
Dividend to stock holders	*= Rs. 12 × 10⁶/year*
Energy loss in transmission	*= 10%*
Diversity factor	*= 1.5*
Load factor	*= 80%*
Maximum demand	*= 14 MW*

Devise a two-part tariff and find the average cost kW-hr.

Solution. Average load = Maximum demand × load factor

= 14000 × 0.8 = 11200 kW

Energy generated per year = $11200 \times 8760 = 98 \times 10^6$ kW-hr.

Cost of the plant = $15 \times 1000 \times 12000$ = Rs. 180×10^6

Interest, insurance depreciation charges of plant

$$= \frac{10}{100} \times 180 \times 10^6 = \textbf{Rs. } \mathbf{18 \times 10^6}$$

Interest, insurance, depreciation charges of primary and secondary equipments

$$= \frac{5}{100} \times 180 \times 10^6 = \textbf{Rs. } \mathbf{9 \times 10^6}$$

Total fixed cost = Insurance, interest and depreciation costs + dividend to stock-holders

$= 18 \times 10^6 + 9 \times 10^6 + 12 \times 10^6$

= **Rs. 39 × 10⁶**

Sum of individual maximum demand

= Max. demand × diversity factor

= 14000 × 1.5 = 21000 kW

∴ Fixed charge per kW = $\frac{39 \times 10^6}{21000}$ = **Rs. 1857**

Total variable charges = all maintenance costs + salaries and wages + Fuel cost

Fuel cost $= 80 \times 10^3 \times 800 =$ Rs. 64×10^6 per year

$\therefore$ Total variable charges $= 0.8 \times 10^6 + 6 \times 10^6 + 2 \times 10^6 + 64 \times 10^6$

$=$ **Rs. 72.8×10^6**

Energy transmitted = Energy generated × transmission efficiency

$= 98 \times 10^6 \times 0.9 = 88.2 \times 10^6$ kW-hr

$\therefore$ Charges for energy consumption $= \dfrac{72.8 \times 10^6}{88.2 \times 10^6} \times 100 =$ **Rs. 0.825/kW-hr.**

Total charges = Fixed charges + variable charges

$= 39 \times 10^6 + 72.8 \times 10^6$

$=$ Rs. 111.8×10^6

Average cost of supply $= \dfrac{111.8 \times 10^6}{88.2 \times 10^6} \times 100 =$ **Rs. 1.27/kWh.**

Problem 34.25. *A peak load on the thermal power plant of 12 MW capacity is 10 MW. The plant annual load factor is 0.7. Taking the following data, design a two-part tariff and overall cost of generation in Rs./kWh :*

Cost of the plant	*= Rs. 17000/kW installed capacity*
Interest, depreciation and insurance	*= 10% of the capital cost*
Cost of transmission and distribution system	*= Rs. 3×10^6*
Interest, depreciation on distribution system	*= 5%*
Operating cost	*= Rs. 3×10^6/year*
Cost of coal	*= Rs. 800/ton.*
Plant maintenance cost	*= Rs. 0.3×10^6/year (fixed) and Rs. 350000/year (running)*
Coal used	*= 30×10^3 tons/year.*

Assume transmission and distribution costs are to be charged to generation.

Solution.

No.	*Items*	*Fixed cost Rs. per year*	*Running cost Rs. per year*
1.	Interest, depreciation etc. of the plant	$\frac{10}{100} \times 17000 \times 12000$ = **20.4×10^6**	—
2.	Interest, depreciation etc. of the transmission and distribution	$\frac{5}{100} \times 3 \times 10^6$ = **0.15×10^6**	—
3.	Annual cost of coal	—	$50 \times 800 \times 10^3$ = **40×10^6**
4.	Operating cost	—	**3×10^6**
5.	Plant maintenance cost	= **0.3×10^6**	**0.35×10^6**
	Total cost	20.85×10^6	43.35×10^6

$\therefore$ Grand total cost

= Fixed cost + Running cost

$= (20.85 + 43.35) \times 10^6 =$ **Rs. 64.2×10^6/year.**

Energy generated/year

$= \text{Average load} \times 8760$

$= (\text{Peak load} \times \text{L.F.}) \times 8760$

$= 10 \times 10^3 \times 0.7 \times 8760 = \mathbf{61.32 \times 10^6\ kWh.}$

$\therefore$ Two part tariff $= \dfrac{\text{Fixed cost}}{\text{Max. load}} + \dfrac{\text{Running cost}}{\text{Energy generated}}$

$= \dfrac{20.85 \times 10^6}{10 \times 10^3} + \dfrac{43.35 \times 10^6}{61.32 \times 10^6}$

$= \mathbf{Rs.\ 2085/kW + Rs.\ 0.707/kWh.}$

Overall cost/kWh $= \dfrac{64.2 \times 10^6}{61.32 \times 10^6} = \mathbf{Rs.\ 1.05.}$

Problem 34.26. *A small generating unit of 5000 kW capacity supplies the following loads :*
(a) Domestic consumers with a maximum demand of 3000 kW at a load factor of 20%.
(b) Small industrial load with maximum demand of 1800 kW at a load factor of 50%.
(c) Street-light load with maximum demand of 200 kW at 30% load factor.
Find the overall energy rate for each type of consumer using the following data :
Capital cost of the plant = Rs. 18000/kW of installed capacity
Total running cost = Rs. 6.2×10^6 per year
Annual rate of depreciation and interest on capital cost is 10%.

Solution. The energy supplied per year to all three consumers

$= (3000 \times 0.2) \times 8760 + (1800 \times 0.5) \times 8760 + (200 \times 0.3) \times 8760$

$= 600 \times 8760 + 900 \times 8760 + 60 \times 8760$

$= \mathbf{1560 \times 8760\ kW\text{-}hrs.}$

$\therefore$ Operating charges per kW-hr $= \dfrac{6.2 \times 10^6}{1560 \times 8760} = \mathbf{Rs.\ 0.453.}$

Capital cost of the plant $= 5000 \times 18000 = \text{Rs. } 90 \times 10^6$

Fixed charges per year $= 90 \times 10^6 \times \dfrac{10}{100} = \text{Rs. } 9 \times 10^6$

$\therefore$ Fixed charges per kW $= \dfrac{9 \times 10^6}{5000} = \mathbf{Rs.\ 1800}$

(*a*) For domestic consumers, the total charges

$= \text{Fixed charges} + \text{operating charges}$

$= 3000 \times 1800 + 600 \times 8760 \times \text{Rs. } 0.453 = (5.4 + 2.38) \times 10^6$

$= \text{Rs. } 7.78 \times 10^6$

$\therefore$ Overall cost per unit

$= \dfrac{7.78 \times 10^6}{600 \times 8760} = \mathbf{Rs.\ 0.15/kW\text{-}hr.}$

(*b*) For industrial consumers, the total charges

$= \text{Fixed charges} + \text{Operating charges}$

$= 1800 \times 1800 + 900 \times 8760 \times \dfrac{4.54}{100} = \text{Rs. } 0.682 \times 10^6$

$\therefore$ Overall cost per unit

$= \dfrac{0.682 \times 10^6}{900 \times 8760} \times 100 = \mathbf{Rs.\ 0.086\ kW\text{-}hr.}$

(*c*) For street lighting load,

Total charges $= \text{Fixed charges} + \text{Operating charges}$

$$= 200 \times 1800 + 60 \times 8760 \times \frac{4.54}{100} = \text{Rs. } 0.384 \times 10^6$$

∴ Overall cost per unit

$$= \frac{0.384 \times 10^6}{60 \times 8760} \times 100 = \textbf{Rs. 0.73/kW-hr.}$$

Problem 34.27. *Determine the load factor at which the cost of supplying a unit of electricity is same in Diesel station as in a steam station if the respective annual fixed and running charges are given below :*

Diesel *Rs. (300/kW + 0.5/kWh).*

Steam *Rs. (1200/kW + 0.125/kWh).*

Solution. P = Maximum load in kW.

K = Load factor (same for both stations).

∴ Average load = $P \times K$.

C_1 (cost of diesel station)

$$= (300\,P + 0.5\,PK \times 8760)$$

C_2 (cost of steam station)

$$= (1200\,P + 0.125 \times PK \times 8760)$$

As given in the problem

Unit energy cost by Diesel = Unit energy cost by steam.

$$\therefore \quad \frac{(300\,P + 0.5\,PK \times 8760)}{8760\,PK} = \frac{(1200\,P + 0.125\,PK \times 8760)}{8760\,PK}$$

$$\therefore \quad 300 + 0.5\,K \times 8760 = 1200 + 0.125\,K \times 8760$$

$$\therefore \quad 8760\,K\,(0.5 - 0.125) = 1200 - 300 = 900.$$

$$\therefore \quad K = \frac{900}{8760 \times 0.375} = 0.274 = \mathbf{27.4\%}.$$

(*b*) Find the generation cost of 500 million kWh at this load factor

Average demand $= KP = \dfrac{500 \times 10^6}{8760} = \mathbf{5.7 \times 10^4\ kW}$

$$\therefore \quad P = \frac{5.7 \times 10^4}{0.275} = \mathbf{20.7 \times 10^4\ kW.}$$

∴ Total cost when $P = 20.7 \times 10^4$ kW is given by

$$C_1 = 300 \times 20.7 \times 10^4 + 0.5 \times 20.7 \times 10^4 \times 0.275 \times 8760$$

$$= 62.1 \times 10^6 + 249.3 \times 10^6 = \mathbf{Rs.\ 311.4 \times 10^6.}$$

or

$$= \frac{311.4 \times 10^6}{500 \times 10^6} = \textbf{Rs. 0.623/kWh.}$$

Problem 34.28. *A motor of 30 kW connected to a condensate pump has been burnt beyond economical repairs. Two alternatives have been proposed to replace it by*

Motor A	*Motor B*
Cost = Rs. 60000	*Cost = Rs. 40000*
η at full load = 90%	*η at full load = 85%*
η at 50% load = 86%	*η at 50% load = 82%*

The life of each motor is 20 years and its salvage value is 10% of the initial cost. The rate of interest is 5% annually. The motor operates at full load for 25% of the time and at half load for the remaining period. The annual maintenance cost of motor A is Rs. 4200 and that of motor B is Rs. 2400. The energy rate is Re. 1/kWh.

Which motor will be economical ?

Solution. (*a*) *Motor A*

Salvage value $= \frac{10}{100} \times 60000 =$ **Rs. 6000**

Depreciation $= \frac{60000-6000}{20} =$ Rs. 2700/year.

Interest $= \frac{5}{100} \times 60000 =$ Rs. 3000/year.

Maintenance = Rs. 4200

Energy given to motor $= \frac{\text{Load on motor} \times \text{time in hours}}{\text{Motor efficiency}}$

$\therefore$ Energy cost $= \left[\frac{30}{1} \times \left(8760 \times \frac{25}{100}\right) \times \frac{1}{0.9} + \frac{30}{2} \times \left(8760 \times \frac{75}{100}\right) \times \frac{1}{0.86}\right] \times 1$

= 73000 + 114593 = **Rs. 187593**

$\therefore$ Total cost = 2700 + 3000 + 4200 + 187593 = **Rs. 197493/year**

(*b*) *Motor B*

Salvage value $= \frac{10}{100} \times 40000 =$ Rs. 4000

Depreciation $= \frac{40000-4000}{20} =$ Rs. 1800

Interest $= \frac{5}{100} \times 40000 =$ Rs. 2000.

Maintenance = Rs. 2400.

Energy cost $= \left[\frac{30}{1} \times \left(8760 \times \frac{25}{100}\right) \times \frac{1}{0.85} + \frac{30}{2} \times \left(8760 \times \frac{75}{100}\right) \times \frac{1}{0.82}\right] \times 1$

= 77294 + 120183

= **Rs. 197477/year**

Total cost = 1800 + 2000 + 2400 + 197477 = **Rs. 203677/year.**

Motor *A* is recommended as its annual cost is less than motor *B*.

Problem 34.29. *The maximum demand of an industry is 50 MW and its load factor is 40%. The following proposals are under consideration :*

(a) A steam plant having an initial cost of Rs. 15000/kW and maintenance cost is 20 paise/kWh. The coal of C.V. of 25000 kJ/kg is used. The overall efficiency of the plant is 25%.

(b) A hydro plant having a capital cost of Rs. 30000/kW and running cost of 5 paise/kWh.

Assuming interest and depreciation rate of 12% for steam plant and 9% for hydro plant, determine the price of coal above which steam station is uneconomical.

Solution. Energy required per year

= Peak load × L.F. × 8760

= 50,000 × 0.4 × 8760 = **175.2 × 10⁶ kWh/year**

(*a*) *Steam plant*

Interest and Depreciation

= Capital × interest rate

$= 50 \times 1000 \times 15000 \times \frac{12}{100}$ = **Rs. 90 × 10⁶/year.**

Maintenance $= \frac{2}{100} \times 175.2 \times 10^6$ = Rs. 35 × 10⁶/year.

Assume W_c is the weight of coal in tons used/year.

$\therefore \quad W_c \times 10^3 \times C.V. \times \eta_{overall} = 175.2 \times 10^6$

$\therefore \quad W_c = \frac{175.2 \times 10^6}{10^3 \times 25000 \times 0.25}$ = **101 × 10³ tons/year**

Assume C is the cost of coal in Rs. per kg

∴ Total cost of steam plant = Interest + Maintenance + Fuel cost

$= 90 \times 10^6 + 35 \times 10^6 + 101 \times 10^3\ C$ ...(*a*)

(*b*) *Hydel plant*

Interest and Depreciation = Capital × interest rate

$= 50 \times 10^3 \times 30000 \times \frac{9}{100}$

= Rs. 135 × 10⁶/year

Running cost $= \frac{5}{100} \times 175.2 \times 10^6$ = Rs. 8.75 × 10⁶/year.

Total cost of hydel plant $= 135 \times 10^6 + 8.75 \times 10^6$ ...(*b*)

The steam and hydel stations will be equally economical if the total cost/year remains same.

∴ Equating the values of (*a*) and (*b*)

$$90 \times 10^6 + 35 \times 10^6 + 101 \times 10^6\ C = 135 \times 10^6 + 8.75 \times 10^6$$

$$\therefore \quad (90 + 35 + 101\ C) = 135 + 8.75$$

$$\therefore \quad C = \frac{(135 + 8.75 - 125)}{101}$$

= **Rs. 0.186/kg = Rs. 186/ton.**

Problem 34.30. *An industrial consumer has a choice between low and high voltage supply available at the following rates :*

High voltage—Rs. 450/kW per year + paise 35/kW.

Low voltage—Rs. 470/kW per year + paise 40/kWh.

In order to have high voltage supply, consumer has to install his own transformer which costs Rs. 1000/kW. The losses in the transformer are 3% of full load. Determine the number of working hours per week above which the high voltage supply will be economical. Assume interest and depreciation 10% of capital and working weeks per year = 50.

Assume the load of the consumer is 1 MW.

Solution. Consumer load = 1000 kW.

Required rating of transformer $= \dfrac{1000}{0.97} = 1030$ kW.

Cost of transformer to the consumer $= 1030 \times 1000$ rupees.

Annual interest and depreciation $= \dfrac{1030 \times 1000}{1} \times \dfrac{10}{100} = 103000$ rupees.

Assume power required by the consumer per week $= h$ hours.

$\therefore$ Power used during the year $= 50h$ hours.

(*a*) Number of units consumed from low voltage side if the load is connected to low voltage

$= 1000 \times 50h$ kWh/year.

(*b*) Number of units consumed from high voltage side if the load is connected to high voltage

$= 1030 \times 50h$ hours.

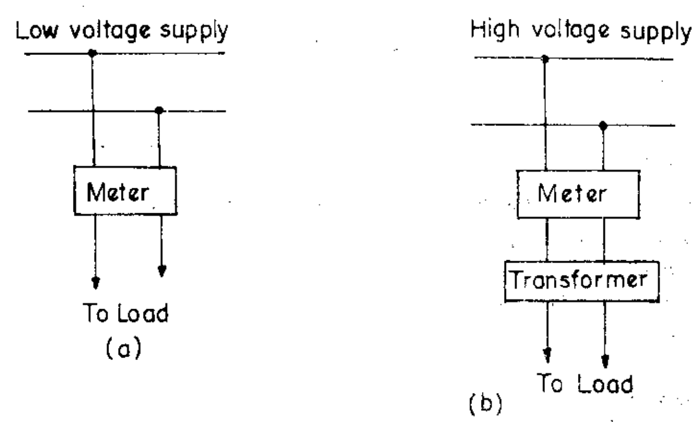


Fig.-Prob. 34.27.

Total cost from low voltage supply in rupees

$$= 1000 \times 470 + \frac{1000 \times 50h}{1} \times \frac{40}{100} = 470000 + 20000h$$

Total cost from high voltage supply in rupees

$$= 1030 \times 450 + \frac{1030 \times 50h}{1} \times \frac{35}{100} + 103000.$$

$$= 566500 + 18025h \qquad ...(b)$$

If both the systems cost is same to the consumer, then

$$470000 + 20000h = 566500 + 18025h.$$

$\therefore$ $h =$ **48.86 hrs/week.**

Problem 34.31. *The maximum load on 2500 kW capacity diesel plant is 1600 kW. The load factor = 0.48.*

Taking the following data, find out the cost of generation in Rs. per kWh.

Installation cost = Rs. 18000/kW. Interest on capital = 15%. Maintenace cost = Rs. 200000/year. Total labour and other consumerables = Rs. 850000 per year. Fuel cost = Rs. 7/kg, lubricating oil cost = Rs. 30/kg. Fuel consumed = 0.25 kg/kWh, oil consumed = 0.025 kg/kWh.

Sol. Capital cost of the plant $= 2500 \times 18000 =$ **Rs.** $\mathbf{45 \times 10^6}$

Interest on capital $= 45 \times 10^6 \times \frac{15}{100} =$ **Rs. 6.75 × 10⁶**

Energy generated per year

$= \text{Max. demand} \times \text{Load factor} \times 8760$
$= 1600 \times 0.48 \times 8760 =$ **6727680 kWh**

Cost of Fuel $= \text{Fuel consumed} \times \text{Cost per unit of fuel}$
$= 0.25 \times 6727680 \times 7$
$=$ Rs. 11773440 per year

Cost of lubricating oil $= \text{Oil consumed} \times \text{Cost per unit of oil}$
$= 0.025 \times 6727680 \times 30 =$ **Rs. 5045760**

Total fixed cost $= \text{Interest} + \text{Maintenance}$
$= 6.75 \times 10^6 + 0.2 \times 10^6 =$ **Rs. 6.95 × 10⁶**

Total running cost $= \text{Fuel cost} + \text{Oil cost} + \text{Running cost}$
$= 11773440 + 5047760 + 850000$
$= \text{Rs. } 17671200 = 17.6712 \times 10^6$

Total cost $= \text{Fixed cost} + \text{Running cost}$
$= (6.95 + 17.6712) \times 10^6 = 24.2212 \times 10^6$

∴ Generation cost $= \frac{24.2212 \times 10^6}{6727680} =$ **Rs. 4.66/kWh**

Problem 34.32. *For a 200 MW thermal power plant, the following data is available :*

(*i*) *Fixed cost = Rs. 24 × 10⁶ per year.*
(*ii*) *Cost of fuel = Rs. 1800 per ton.*
(*iii*) *C.V. of fuel used = 20000 kJ/kg.*
(*iv*) *Other expenses (like salary and consumables) = Rs. 280 per kW per year.*
(*v*) *Plant heat rate*
  (*a*) *18000 kJ/kWh at 100% capacity factor.*
  (*b*) *10500 kJ/kWh at 50% capacity factor.*

Determine the generating cost per kWh at 100% and 50% capacity factor.

Sol. Fixed cost per kW-capacity per year

$$= 160 + \frac{24 \times 10^6}{200 \times 10^3} = 160 + 120 = \textbf{Rs. 280/kW}$$

Capacity factor (C.F.) $= \frac{\text{Average demand}}{\text{Plant capacity}}$

(*a*) **At 100% C.F.**

The average demand $= 200 \times 1000 = 2 \times 10^5$ kW

∴ Energy generated per year at 100% C.F.

$= 200 \times 10^3 \times 8760$ kWh

∴ Fixed cost per kWh $= \left(\frac{280 \times 200 \times 10^3}{200 \times 10^3 \times 8760}\right) \times 100 =$ **3.2 paise**

Coal burned per kWh $= \frac{8000}{16000} = 0.5$ kg

∴ Cost of coal per kWh energy generated

$$= \frac{0.5 \times 1800}{1000} = \textbf{0.9 rupees}$$

∴ Total cost of generation per kWh

= fixed cost + coal cost

= 0.032 + 0.9 = **Re. 0.932**

(*b*) When the plant capacity factor is 0.5, then the energy generated per year

$= (200 \times 10^3 \times 0.5) \times 8760$ kWh

∴ Fixed cost per kWh $= \dfrac{280 \times 200 \times 10^3}{(200 \times 10^3 \times 0.5) \times 8760} \times 100$ paise

= **6.4 paise**

Coal burned per kWh

$= \dfrac{10500}{16000} = \mathbf{0.66\ kg}$

∴ Cost of coal per kWh energy generated

$= \dfrac{0.66 \times 1800}{1000} = \mathbf{1.18\ rupees}$

∴ Total cost of generation per kWh

= 0.064 + 1.18 = **Rs. 1.244**

Problem 34.33. *An installed capacity of a power plant is 210 MW and its capital cost is Rs. 10,000/kW. The fixed cost is 13% of the investment cost. At full load, the variable cost is 1.3 times the fixed cost per year. Assuming the variable cost is proportional to the energy produced, find the generating cost when the plant is running at full load and 50% load.*

Solution. Capital cost of the station

$= 10{,}000 \times 210 \times 10^3 = \text{Rs. } 2100 \times 10^6$

(*a*) **When the plant is operating at full load.**

Fixed cost $= 2100 \times 10^6 \times \dfrac{13}{100} = \mathbf{Rs.\ 273 \times 10^6}$

Variable cost $= 273 \times 10^6 \times 1.3 = \mathbf{Rs.\ 355 \times 10^6}$

Total cost = Fixed cost + Variable cost

$= (273 + 355) \times 10^6 = \mathbf{Rs.\ 628 \times 10^6}$

Total units generated per year

= (Max. demand × Load factor) × 8760

$= 210 \times 10^3 \times 1 \times 8760 = \mathbf{1837.5 \times 10^6\ kWh}$

Generating cost when the plant is running at full load

$= \dfrac{628 \times 10^6}{1837.5 \times 10^6} = \text{Rs. } 0.342 = \mathbf{34.2\ paise/kWh}$

(*b*) When the plant is running at 50% load

Fixed cost $= \text{Rs. } 273 \times 10^6$

Total units generated $= \dfrac{1}{2} \times 1837.5 \times 10^6 = 918.75 \times 10^6$ kWh

As the variable cost is proportional to kWh generated

$= 355 \times 10^6 \times \dfrac{1}{2} = \text{Rs. } 177.5 \times 10^6$

Total operating cost $= \text{Rs. } (273 + 177.5) \times 10^6 = \text{Rs. } 450.5 \times 10^6$

Generating cost $= \frac{450.5 \times 10^6}{918.75 \times 10^6}$ = Rs. 0.49 = **49 paise/kWh**

As the load factor decreases, the cost of generation increases.

Problem 34.34. *A diesel electric station has 4-generating sets, each of 600 kW and 1 of 400 kW capacity. The other data is given below :*

Max. demand = 1600 kW, load factor = 0.45

Capital cost = Rs. 10,000/kW, Annual fixed cost (interest + depreciation + insurance and taxes) = 15% of capital cost

Annual maintenance cost = Rs. 60,000

Operation cost = Rs. 1,00,000

Cost of fuel = Rs. 7/kg, cost of lubricating oil = Rs. 40/kg

Fuel used = 0.5 kg/kWh, lubricating oil used = 0.0025 kg/kWh

CV of fuel used = 42000 kJ/kg, Generator η = 0.92

Determine (a) The rating of diesel engine (b) Energy produced/year (c) Cost of generation Rs./kWh (d) Overall η of the plant.

Solution.

(*a*) Rating of first 3-sets $= \frac{600}{0.92}$ = **650 kW**

Rating of last set $= \frac{400}{0.92}$ = **435 kW**

(*b*) Average demand = Max. demand × Load factor
= 1600 × 0.45 = 720 kW

Energy generated/year = 720 × 8760 = **6.3 × 10⁶ kWh**

(*c*) (*i*) **Fixed costs per year**

Capital cost = (3 × 600 + 1 × 400) × 10,000 = 2.2×10^7

Annual fixed cost = $0.15 \times (2.2 \times 10^7) = 0.33 \times 10^7$

Maintenance cost = 0.06×10^7

Total fixed cost = $(0.33 + 0.06) \times 10^7 = \mathbf{0.39 \times 10^7}$

(*ii*) **Variable costs per year**

Fuel cost = $(6.3 \times 10^6 \times 0.5) \times 7$ = Rs. 22×10^6

Lubricating oil cost = $(6.3 \times 10^6 \times 0.0025) \times 40$ = Rs. 0.63×10^6

Operating cost = Rs. 0.1×10^6

Total variable cost per year

= $(22 + 0.63 + 0.1) \times 10^6$ = Rs. 22.73×10^6

Total cost = Fixed cost + Variable cost
= $(3.9 + 22.73) \times 10^6$ = Rs. 26.63×10^6

Cost per kWh generated

$= \frac{26.63 \times 10^6}{6.3 \times 10^6}$ = **Rs. 4.23**

(*d*) Overall η of the plant

$= \frac{\text{Output}}{\text{Input}} = \frac{6.3 \times 10^6 \times 3600 \text{ (kJ)}}{6.3 \times 10^6 \times 0.5 \times 42000} = 0.1714 = \mathbf{17.14\%}$

Problem 34.35. *The annual costs of operating 30 MW gas-turbine power plant as base load are as follows :*

Plant cost = Rs. 10 crore, Interest and insurance = 13%
Depreciation = 5%, Plant maintenance cost = Rs. 50 lac
Fuel cost = Rs. 700 lac, Lubricating cost = Rs. 25 lac
Labour cost = 75 lac. Max. demand = 25 MW
L.F. = 0.75, Profit expected = 5 paise/kWh
Determine the cost of electricity generated considering the profit.

Solution. Average load = Max. load × L.F.
$= 25 \times 0.75 = \mathbf{18.75\ MW}$

Energy generated per year
$= (18.75 \times 10^3) \times 24 \times 365 \text{ kWh} = \mathbf{1.6425 \times 10^8\ kWh}$

Interest and insurance cost $= \frac{13}{100} \times 10 \times 10^7 = \mathbf{Rs.\ 13 \times 10^6}$

Depreciation $= \frac{5}{100} \times 10 \times 10^7 = \mathbf{Rs.\ 5 \times 10^6}$

Plant maintenance cost = Rs. 50×10^5
Fuel cost = Rs. 700×10^5
Lubricating cost = Rs. 25×10^5
Labour cost = Rs. 75×10^5

Profit required $= \frac{5}{100} \times (1.6425 \times 10^8) = \text{Rs. } 8.2125 \times 10^6$

Total cost $= 13 \times 10^6 + 5 \times 10^6 + 5 \times 10^6 + 70 \times 10^6 + 7.5 \times 10^6 + 8.2125 \times 10^6$
= Rs. 111.2125×10^6

Cost of energy generated (paise/kWh)

$$= \frac{(111.2125 \times 10^6) \times 100}{1.6425 \times 10^8} = \mathbf{67.7\ paise/kWh}$$

EXERCISES

34.1. What is meant by power plant economics ? What are the fixed and operating costs ?
34.2. Discuss in detail how the load between two alternators of generating station can be divided for the best economy.
34.3. What is the significance of incremental rate for a power plant ?
34.4. Discuss the methods of determining the depreciation of electrical power plant.
34.5. Explain the effect of load factor of an electric power station on the cost per kW-hr generated.
34.6. Keeping in view the operating and fixed costs of a power station, suggest some suitable tariffs.
34.7. What is the significance of two part tariff and three part tariff ? Explain the advantages of each over other.
34.8. What is the protection provided to a power plant against the consumers having :
(*a*) high maximum demand with poor load factor
(*b*) high maximum demand with poor power factor
(*c*) low demand with high kVA demand
34.9. The cost of generating unit is 1,20,000 rupees and its expected life is 12 years. If it is to be recovered with an interest rate of 6%, find the amount of each instalment assuming the salvage value of 16000 rupees if
(*a*) interest is charged annually
(*b*) interest is charged semi-annually
(*c*) interest is charged quarterly.
Use sinking fund method.
34.10. The value of the new industrial plant is Rs. 5×10^6 and its salvage value is Rs. 5×10^5 at the end of 15 years. Determine the value of the plant at the end of 8 years using the following methods of depreciation · (*a*) Straight line method (*b*) Reducing balance method and (*c*) Sinking fund method at 10% compounded annually.
[Ans. (*a*) Rs. 2.6×10^6 (*b*) Rs. 1.4645×10^6 (*c*) 1.42×10^5**]**

34.11. The cost of a small power station is Rs. 1.5×10^6 and money for its construction is borrowed at 10% interest. A sinking fund with interest at 7.5% is to be provided to repay the whole loan at the end of 20 years with a salvage value of Rs. 50×10^3. The management charges are Rs. 150000/year and running cost is 80 paise/kWh. Determine the annual sum which will have to be paid into the sinking fund and total annual fixed charges on the station.

Input-Output Curves

34.12. The input-output characteristics of a 10 MW thermal station are given by

$$I = 5 \times 10^6 (10 + 8L + 0.4L^2)$$

where I is in kJ/hr and L is in MW.

Find : (*a*) the load at which the plant runs at maximum efficiency.

(*b*) the increase in input required to increase the output from 3 to 5 MW by using input-output curve and by incremental rate curve. Comment on the results.

34.13. The input-output curve of 20 MW generating station is given by the following equation :

$$I = (7.5 + 0.125\ L + 0.16\ L^2)\ 5 \times 10^6$$

where I is in kJ/hr and L is in MW. Find the average heat rate of this station for a day when it was operating at load of 20 MW for 12 hours and was kept hot at zero load for the remaining 12 hours. Find the saving in the heat rate if the same energy is produced for the whole day at 100% load factor.

34.14. The input-output curve of a 150 MW station is given by the following expression :

$$I = 5 \times 10^6 (60 + 1.25\ L + 0.01\ L^2)$$

(*a*) Plot input-output heat rate and incremental rate curve.

(*b*) Find the load at which minimum heat-rate occurs, and check with the plot.

(*c*) Find the area under incremental rate curve in kJ per hour between the loads 0 and 120 MW.

34.15. Turbogenerator units *A* and *B*, each of 10 MW capacity have the following input-ouput characteristics :

Unit A $\quad I_a = 5 \times 10^6 (2.5 + 2.25\ L_a)$

Unit B $\quad I_b = 5 \times 10^6 (5 + 2\ L_b)$

where I is in kJ/hr and L is in MW.

(*a*) If either unit were to be placed in operation alone, which should be selected ? Why ?

(*b*) Devise a loading schedule with 5 MW steps for the most economical operation when both units are operating in parallel.

34.16. A 10 MW diesel engine has the following heat-rate curve :

$$HR = 5 \times 10^6 \left(\frac{5}{L} + 1 + 0.1\ L + 0.0025\ L^2 \right)$$

where HR is in kJ/MW-hr and L is in MW.

The annual load requirements are tabulated below :

Load in MW	10	8	7.6	7.4	7.0	5.0	2.0	1.0	0.0
No. of hours at load	0	500	1000	3000	3500	10,000	7000	8000	8000

At zero load, the engine is shut-down.

Find the annual average heat rate for the engine using the average load for 200 hours.

Economical Loading of Units

34.17. The incremental fuel costs for two generating units *A* and *B* of a thermal power plant are given below :

$$\frac{dF_a}{dP_a} = 0.06\ P_a + 11.4$$

$$\frac{dF_a}{dP_b} = 0.07\ P_b + 10$$

where P is in MW and F is in rupees per hour. Find (*a*) the economic loading of the two units when the total load supplied by the station is 150 MW and cost of supply per hour.

(*b*) The loss in fuel cost per hour if the load is equally shared by the two units.

[**Ans.** (*a*) $P_a = 70$ MW, $P_b = 80$ MW (*b*) Rs. 163 per hour]

34.18. The incremental fuel costs for three generating units A, B and C of a thermal power plant are given below :

$$\frac{dF_a}{dP_a} = 0.06\,P_a + 12,\quad \frac{dF_b}{dP_b} = 0.07\,P_b + 10,\quad \frac{dF_c}{dP_c} = 0.08\,P_c + 8,$$

where P is in MW and F is in rupees per hour.

Find the most economical loading of the units when the total load supplied by the station is 200 MW. If all are equally loaded, find the loss in fuel cost per hour.

Economic Selection of Generating Unit

34.19. To serve the load having the annual load characteristics are tabulated below :

Load in kw	5000	4000	2000	1000	500
No. of hours at load	200	4000	2000	1000	1560

The steam and diesel plants are considered to supply the load required.

The performance characteristics of Diesel and steam are given below :

Steam $I = 5 \times 10^6\,(1.5 + 2L + 0.028\,L^3)$

Diesel $I = 5 \times 10^6\,(2.25 + L + 0.13\,L^2 - 0.004\,L^3)$

where I is input in kJ/hr and L is load in MW.

Decide which plant will be more economical.

34.20. The costs of coal and diesel oil are Rs. 850 and Rs. 2500 per tonne respectively. The calorific values of coal and diesel are 20,000 kJ/kg and 45,000 kJ/kg respectively.

The capital cost of steam plant = Rs. 9800/kW
The capital cost of diesel plant = Rs. 8700/kW
The fixed charges for both plants = 12% of capital cost.

The steam plant requires few more men for operation than diesel and their annual salary is Rs. 125×10^6. Which plant should be selected and why ?

34.21. A load having a maximum demand of 100 MW at 30% load factor may be supplied by one of the following schemes :

(*a*) A steam plant capable to supply the whole load.

(*b*) A steam plant in conjunction with a pumped storage plant capable of supplying 10^6 kW-hr energy per year with a maximum load of 40 MW.

Using the following data, find most economical scheme among the two ;

Capital cost of steam station
= Rs. 10000/kW of installed capacity
Capital cost of pump-storage station
= Rs. 7000/kW of installed capacity
Operating cost of steam station = 50 paise/kW-hr
Operating cost of pump storage station = 5 paise/kW-hr.

Interest and depreciation together on the capital cost is 15% for both schemes. Assume that no reserve capacity is required.

34.22. A factory requires maximum demand of 850 kW at 20% load factor. This load can be supplied either by diesel generating plant or by public supply. Using the following data, find the economical choice among the two.

Diesel plant

Cost of plant = Rs. 960×10^7
Fuel consumption = 0.3 kg per kW-hr
Cost of fuel = Rs. 800/tonne
Cost of lubricating oil and water used = 1.5 P./kW-hr generated
Salaries and wages = Rs. 135000 per year
Interest and depreciation = 12% of capital cost.

Public supply

It charges Rs. 55/kW of maximum demand and 80 P. per kW-hr.

34.23. The capital costs of steam and hydel power stations are Rs. 20000 and Rs. 21000 per kW of installed capacity respectively. The running costs of steam and hydel stations are 50 paise/kWh and 32 paise/kWh respectively. The reserve capacities of the steam and hydel stations are 25% and 32.3% of the installed capacity respectively.

At what L.F. would the overall cost per kWh be the same for both plants ?

Assume interest and depreciation charges 9% for steam and 7.5% hydel station.

Also calculate the generating cost of 500 million units at this load factor.

34.24. The load of a particular area is 120 MW at 40% load factor. It has to be supplied by either

(*a*) Steam station alone whose capital cost is Rs. 15000/kW and operating cost is 6 P/kWh.

or (*b*) by steam and hydel stations. The energy supplied by hydel-plant is 120×10^6 kWh/year. Maximum generating capacity of hydel is 45 MW. Its capital cost is Rs. 6000/kW and operating cost is 1.5 paise/kWh.

Take interest on capital 12% per year for both proposals. Calculate the overall generating cost per kWh if no spare plant capacity is required in both cases.

34.25. A maximum load of 100 MW with 50% L.F. can be supplied either by steam power plant or hydel power plant. Taking the following data , calculate the price of coal above which steam station is uneconomical.

(*a*) Hydro capital cost—Rs. 15000/kW and running cost—10 paise/kW.

(*b*) Thermal capital cost—Rs. 10000/kW and maintenance cost—40 paise/kWh.

Coal used has a colarific value of 30,000 kJ/kg. The overall efficiency of thermal plant is 26%.

Take interest and depreciation as 10% for both the plants.

34.26. The maximum demand of a factory is 100 MW and estimated L.F is 62%. The energy to the factory can be supplied by either

(*a*) A steam power station having a capital cost of Rs. 9200/kW and maintenance cost of 20 paise/kWh. The coal used has c.v. of 20,000 kJ/kg and overall efficiency of the plant is 25%. *Or*

(*b*) A hydro station having a capital cost of Rs. 25000/kW and running cost 5 paise/kWh.

Allowing 12% for steam plant and 10% for hydro plant for interest and depreciation, calculate the price of the coal above which steam station becomes uneconomical.

34.27. A steam plant and diesel plant are being compared each having a capacity of 1000 kW. The load to be served is tabulated below :

Load in kW	1000	800	500	200
No. of hours at load	100	1000	6000	1660

The performance characteristics of the plants are :

Steam $I = (300 \times 30^3 + 1500\ L + 0.25\ L^2 + 0.001\ L^3) \times 5$

Diesel $I = (280 \times 10^3 + 1500\ L + 0.60\ L^2 + 0.0002\ L^3) \times 5$

where I is in kJ/hr and K is in kW.

The cost of coal	= Rs. 1200/tonne
The cost of oil	= Rs. 3000/tonne
C.V. of coal	= 30,000 kJ/kg
C.V. of oil	= 45000 kJ/kg
The annual salary of crew men for thermal plant	= Rs. 50,0000
The annual salary of crew men for diesel plant	= Rs. 32,0000
Maintenance of steam plant	= Rs. 36,0000/year
Maintenance of diesel plant	= Rs. 24,0000/year
Capital cost of steam plant	= Rs. 8000/kW
Capital cost of diesel plant	= Rs. 12000/kW

Which plant is more economical if the fixed charge rate for both plants is 15% ?

34.28. The data given below have been collected for comparing two proposed installations of 1000 kW capacity each :

	Steam Plant	Diesel Plant
Fuel cost per 10^6 kJ	Rs. 50	Rs. 65
Annual maintenance cost	Rs. 200000	Rs. 30000
Annual labour cost	Rs. 1800×10^3	Rs. 1600×10^3
Annual supplies cost	Rs. 500000	Rs. 400000
Unit installation cost	Rs. 24000/kW	Rs. 18000/kW

The characteristics of load are given below :

Load in kW	1000	800	500	200
No. of hours at load	100	1000	6000	1660

Plant performance characteristics are

Steam $I = (300 \times 10^3 + 1500\,L + 0.25\,L^2 + 0.101\,L^3) \times 5$

Diesel $I = (280 \times 10^3 + 1500\,L + 0.6\,L^2 + 0.0002\,L^3) \times 5$

where I is in kJ/hr and L is in kW

At fixed charge rate of 11% which plant is economical and why ?

34.29. A village is considering the installation of a 1500 kW capacity municipal plant composed of two diesel engines. Three different plans of installation are proposed as given below :

Plant	*Total installed cost per kW in rupees*	*Input-output characteristics*
A	16000	$I = (625 \times 10^3 + 1200\,L + 0.0015\,L^3) \times 5$
B	18400	$I = (476 \times 10^3 + 1000\,L + 0.0015\,L^3) \times 5$
C	20000	$I = (350 \times 10^3 + 750\,L + 1.5\,L^2 - 0.001\,L^3) \times 5$

where I is in kJ/hr and L is in kW.

The annual load requirements are tabulated below :

Load in kW	1400	1000	500	100
No. of hours at load	1000	4000	1000	2760

Oil is available at Rs. 2100 per tonne with a heating value of 45000 kJ/kg. If the fixed charge rate is 11%, which plant is economical and why ?

34.30. A factory requires 700 kW power at 25% load factor. The following two supplies can be considered.

Public supply

Public supply tariff is Rs. 400/kW of maximum demand and 20 P. per kW-hr.

The capital investment for the equipments = Rs. 700000

Interest and depreciation = 10% of capital cost

Private oil engine generating station

Capital investment = Rs. 2500×10^3

Interest and depreciation = 15% of capital cost

Fuel consumption = 0.3 kg/kW-hr

Cost of fuel = Rs. 700/tonne

Wages + repair + maintenance cost = 7 P./kW-hr generated

Choose the economical supply.

34.31. Two lamps of given specifications are to be compared :

(*a*) cost of first lamp is Re. 10 and it takes 100 watts,

(*b*) cost of second lamp is Rs. 40 and it takes 60 watts.

Both lamps are of equal candle power and each has a useful life of 1000 hours. Which lamp will prove economical if the energy is charged at Rs. 700/kW of maximum demand per year plus 5 P. per kW-hr ?

At what load factor both lamps will be equally advantageous ?

Generation Cost Calculations

34.32. Find the monthly bill of a consumer and unit energy cost for a total consumption of 1600 kW-hr and maximum demand of 10 kW. Use the Hopkinson demand rate as given below :

Demand rates

First 1 kW of maximum demand	= Rs. 150/kW/month
Next 4 kW maximum demand	= Rs 120/kW/month
Excess over 5 kW of maximum demand	= Rs. 100/kW/month

Energy rates

7—50 kW-hr	51—100	101—400	401—900	over 900
175 P./kW-hr	120 P./kW-hr	80 P./kW-hr	60 P./kW-hr	40 P./kW-hr

Also find the lowest possible bill for a month of 30 days and unit energy cost for the given energy consumption.

[*Hint* : The lowest possible bill will occur when Average load = Maximum load].

34.33. A Hopkinson demand rate is quoted as follows :

Demand rate

First 1 kW of maximum demand	= Rs. 50/kW/month
Next 4 kW of maximum demand	= Rs. 40/kW/month
Excess over 5 kW of maximum demand	= Rs. 30/kW/month

Energy rates

First 50 kW-hr	= 160 P./kW-hr
Next 50 kW-hr	= 140 P./kW-hr
Next 200 kW-hr	= 130 P./kW-hr
Next 400 kW-hr	= 120 P./kW-hr
Excess over 700 kW-hr	= 100 P./kW/hr.

(*a*) Find the monthly bill for a total consumption of 1500 kW-hr and a maximum demand of 12 kW. Also find the unit energy cost.

(*b*) If the month contains 30 days, find the lowest possible bill and corresponding unit energy cost.

34.34. The annual costs of a 15 MW capacity thermal power plant are given below :

Cost of plant	= Rs. 9000/kW of installed capacity
Depreciation charges	= 5% of plant cost
Interest + Insurance	= 5% of plant cost
Cost of primagny & Secondary distribution	= Rs. 14×10^6
Interest + insurance + taxes + depreciation of primary and secondary distribution systems	= 5% of plant cost
Maintenance cost of primary and secondary	= Rs. 1.8×10^6

Plant maintenance costs are given below :

Fixed costs	= Rs 30×10^4
Variable cost	= Rs. 40×10^4
Operating cost	= Rs. 6×10^6
Consumption of coal	= 30,000 tonnes
Cost of coal	= Rs. 600 per tonne
Dividend to stock-holders	= Rs. 10×10^6
Energy loss in transmission	= 10%
Maximum demand	= 14 MW

Diversity factor	= 1.5
Load factor	= 0.7

Devise a two part tariff for the above given expenses.

34.35. Work out a *two part tariff* and overall generation cost in Rs./kW-h from the following data for a generating station :

Capacity of plant	= 100 MW
Capital cost	= Rs. 15000/kW
Maximum demand	= 50 MW
Annual L.F.	= 0.4
Interest and depreciation	= 10% of capital cost/year
Annual salaries	= Rs. 400×10^4
Annual fuel cost	= Rs. 350×10^4
Annual cost of operation and maintenance	= Rs. 150×10^4

34.36. Design a two part tariff for the consumers from the following data :

Consumers' maximum demand	= 25 MW
Capital cost	= Rs. 12000/kW
Annual load factor	= 0.4
Annual salaries and wages	= Rs. 200×10^4
Annual maintenance and repairs	= Rs. 150×10^4
Annual fuel cost	= Rs. 2000×10^4
Losses in transmission and distribution	= 10%
Interest and depreciation	= 10% of capital
Load diversity factor	= 1.4

34.37. The expected annual cost of power system supplying the energy to 40,000 consumers is tabulated below :

Fixed (charges)	= Rs. 2400×10^4
Energy charges	= Rs. 1716×10^4
Consumers charges	= Rs. 210×10^4
Profit	= Rs. 168×10^4
Maximum demand	= 5000 kW
Diversity factor	= 4
Energy supplied	= 17×10^6 kW-hr.

Devise a three part tariff allowing 25% of the profit in fixed charges, 50% in energy charges and remaining 25% in customer charges.

34.38. Find the cost of generation per kW-hr from the following data :

Station capacity	= 100 MW
Capital cost	= Rs. 12000/kW-installed
Annual charges	= 10% of capital
Fuel consumption	= 0.7 kg/kW-hr
Cost of fuel	= Rs. 500/tonne
Salaries and wages	= Rs. 600×10^4
Maximum demand	= 60 MW
Load factor	= 30%

34.39. A power station has an installed capacity of 20 MW. The cost of the plant is Rs. 12000/kW installed. The fixed charges are 13% of the investment. At 100% load factor, the variable costs of the station per year are 1.5 times the fixed costs. Assuming there is no reserve capacity and variable costs are proportional to the energy production, find the cost of generation at 100%, 80%, 60%, 40% and 20% load factor. Plot the curve.

□□□

35

Combined Operation of Different Power Plants

35.1. INTRODUCTION

It is the aim of the national economy to create the maximum amount of generating capacity with the available funds and to generate power at as cheap rate as possible. Power supply industry is highly capital-intensive and therefore it is desirable to utilise in optimum manner once generating facilities become available. Before the investment of huge amount in this industry, the most economic generating scheme should be selected to supply power at lowest cost. Once the generating facilities (different power plants) are made available, it is important to have integrated operation of neighbouring power systems so that maximum energy generation takes place from power stations like thermal and nuclear and maximum energy and capacity are utilised from the hydrostations. This can be only achieved by closely combined operation of different power systems which if operated individually cannot be utilised to the maximum advantage. Therefore, it is necessary that the power systems of the different states must be interconnected to yield the maximum benefit.

There was acute power shortage in Punjab, Haryana and U.P. in the year 1970-71. This was partly due to the loads having been built up beyond firm capacity available and secondary the run-off in Bhakra reservoir in 1969 corresponded to that of a dry year. Fortunately there was surplus capacity of 180 MW at Satpura Thermal Station in M.P. but unfortunately this power could not be supplied to deficit states as interconnected transmission facilities were not available.

The U.S. national power survey estimated that the reserve capacity of power systems required in U.S. can be reduced from 17% to 8% by 1981, with the same reliability if fully coordinated operation of all the country's resources was carried out. In India also, the reserve capacity requirements can be considerably reduced by having fully coordinated operation.

Interconnected power system can provide large savings both in capacity and fuel cost. In order to achieve optimum utilisation of resources and at the same time ensuring reliability and continuity of power supply, proper administration and technical set-up has to be created.

No doubt, the rapid pace of interconnection between the power systems can greatly improve the continuity, security and integrity of power supply if it is associated with sound mechanism for monitoring and control.

35.2. ADVANTAGES OF COMBINED WORKING

When the number of stations (hydro, thermal, nuclear etc.) work in combination with each other to supply the power to the consumers, the system is known as an 'Interconnected system'. In an interconnected system, a number of power stations can be operated with great reliability and economy.

The advantages of combined system over a single power plant are listed below :

(1) The reliability of supply to the consumers is much greater in interconnected system than in an isolated system with only one power station. The reliability of hydro-station with reference to the capacity available is dependent on the river flow and storage available at any time during the year dependent on and the reliability of thermal station is the frequency of mechanical and electrical failures.

The overall reliability of hydro-station is more than the thermal station.

(2) The interconnection of different power plants reduces the amount of generating capacity required to be installed as compared to that which would be required without interconnection. Because there is a certain diversity in time between peak demands of two systems, so that the peak load of the combined system is less than the sum of individual peaks.

(3) In the event of power failure at one of the stations in the interconnected system, the consumers can be fed from the other station to avoid complete shut-down.

(4) The spinning reserve required is reduced by interconnection. Because each system individually operated must carry its own reserve capacity but by interconnecting, the reserve of the system may be sufficient to serve for both.

(5) The overall cost of energy per unit of an interconnected system is less.

Benefits that can be obtained from a combined system are flexibility of operation, better utilization of hydro-power, security of supply and reduction in the spare plant capacity.

It is always necessary to evaluate the composite effect of all the diversities to determine the capacity benefits resulting from interconnection. The diversities exist due to occurrence of peak demand at different times during the day, seasonal reduction in load carrying capacity of the hydro-plant and shut-down of some units for maintenance and repair. The composite effect of diversities in interconnected system can be evaluated by probability methods.

(6) Integrated systems facilitate more effective use of transmission line facilities at higher voltage due to group of generating stations being tied.

(7) Integrated system requires less capital investment and less expense for supervision, operation and maintenance.

(8) Peaking capacities can be planned on a joint basis in an interconnected system so that the peak loads of combined system can be carried out at a much lower cost than what is possible with small individual system.

35.3. LOAD DIVISION BETWEEN POWER STATIONS

It is common practice to serve to the load curve by interconnected system which has a very high peak demand. In such case, the load curve is generally divided into two parts as base load and peak load. In an interconnected system, base load is supplied by one plant and the peak load is taken by the other plant. In such system, it is not necessary to interconnect the two power plants of the same type. For example, say the base load is taken by steam plant then it is not necessary to take the peak load by steam plant. The peak load may be taken either by hydro or diesel plant.

The main purpose of interconnection is to distribute the load among the interconnected system in order to achieve the overall economy.

The base load is generally taken by steam power plant and peak load by hydro-power plant. But the hydro-plant can very well be used for supplying the peak load as well as base load also. When the base load is taken by hydro-plant, the peak load can be supplied by steam station or a diesel station or any other suitable unit.

The selection of the power station as a base load plant or peak load plant depends upon its characteristic and ability of the power plants to meet the requirements.

The requirements of a plant supplying the base load are listed below :

(1) The working and maintenance cost of the plant should be minimum as it has to work for most of the time during the year.

(2) It must be capable to supply the load continuously.

(3) Capital cost of the plant should be minimum and it should be located easily near the load centre to reduce the transmission loss.

(4) The number of operators required should be minimum.

(5) The spares and repair facilities should be readily available.

As far as hydro-power plants are concerned, the operating cost of the plant is minimum as no fuel is required for the purpose of power generation. The cost of maintenance is also minimum compared with other power plants. The major problem in case of hydro-plant is the high capital cost requirement for its construction and many times prohibitive. The hydro-plants cannot be located near the load centre as its location is controlled by the natural conditions of topography. The power generating capacity of the plant also depends on the availability of the water which again depends on the natural phenomenon of rain.

As far as steam power plants are concerned, the capital cost of the plant is less than hydro-plant and it has an advantage of locating the plant near load centre which reduces the transmission capital cost and transmission loss also. However, the maintenance cost is higher than hydro-power plant.

As far as nuclear power plants are concerned, they are invariably used for base load as maximum economy can be achieved only when these are used as base load plants.

Diesel and gas turbine plants are never considered for base load due to limited unit generating capacity.

The requirements of plant to take the peak loads are listed below :

(1) The capital cost of the plant should be minimum.

(2) It must have quick response to the change in load.

(3) The plant should be capable of being started from cold conditions within minimum time.

(4) The operating cost should not be high.

The hydro-plant is best suited as peak load plant as it can be easily started from cold and its response is very high. Hydro-power stations are used for meeting the peak load in interconnected system when the quantity of water available for power generation is limited. The major drawback of hydro-power to use as a peak load plant is high capital cost. It is not used for a longer period during the year as peak occurs for a short period of the year and therefore heavy capital cost is not justified.

The stand-by units in steam plants are used to take the peak loads. The major drawback of steam plant to use as peak load plant is poor response to the change of load. The nuclear power stations are never used as peak load plants for the reason already mentioned.

Diesel and gas turbine plants can be used as peak load plants, as their response to the load is high, they can be started quickly from cold, capital cost is not very high. The maintenance cost is low as number of auxiliaries required is less. These plants have good overload capacity (minimum 10%) and high thermal efficiency compared with steam plant. Therefore, their operating charges are low.

If an interconnected system is used to supply the load, the next problem is division of load among the power plants. The load distribution among the power plants depends upon the operating characteristics of the power plants. The distribution of load among the power plants in an interconnected system is done in such a way that the overall economy is achieved.

Analysis of Load Sharing between Base Load and Peak Load Stations. Consider the load duration curve as shown in Fig. 35.1. It is not economical to design a plant to load to the maximum peak load as it works in under-load condition for most of the time.

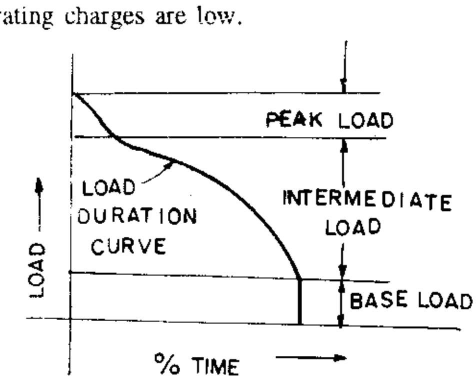


Fig. 35.1.

In order to achieve maximum possible economy in meeting the system requirements, the guiding principle is the loading of the most efficient power station in the order of merit of low fuel cost. This is made possible by establishing central control room which can control number of stations simultaneously in the grid system.

The start-up and shut-down in the order of fuel cost is done by the control system. Parallel operation of stations and the co-ordination of the generation of electricity leads to considerable saving in comparison with loads fed by independent power stations. In addition to the saving in fuel consumption effected by concentrating generation in the most efficient stations for most of the possible times, there is also saving due to reduced spare capacity required and also due to the employment of large size units.

Based on the above principle, the whole area under the load curve is divided into three parts as base load, intermediate load and peak load and these loads are also taken by respective power plants. Base load station takes up the load on the lower region of the load curve. This station is highly efficient and operates on three shift basis throughout the year. The fixed cost of these plants is usually high. Capacity factor is the index of the return on the capital investment on the plant. Therefore, continuous operation of base load stations at high load factor improves the capacity factor of these stations and this makes operation of the costly (but efficient) plant an economic proposition. Hydro and nuclear power stations are usually classified as base load stations. Intermediate stations operate on two or single shift basis. The capital cost of these stations is lower and fuel cost is higher than base load plants. Thermal stations fall under this category.

Peak load stations operate only when required for short times under the upper part of the load curve. As they operate for short period, their plant capacity factor is very low. Therefore, the fuel cost of such plants is highest but total capital cost is less. In the event of sharp peak load for a short duration, the efficiency of the plant matters little. Diesel and Gas turbine plants are classified under this category.

For a known load duration curve, we can find out the most economic load sharing between base load and peak load stations operating in parallel and whose operating costs are known.

Let the operating costs are

$C_1 = A_1.\text{kW} + B_1.\text{kWh}$ (base load)

$C_2 = A_2.\text{kW} + B_2.\text{kWh}$ (peak load)

P = Peak load of the system (kW)

Q = Total number of units generated by the system (kWh).

P_b = Peak load on base load plant.

Q_b = Units generated by base load plant

$\therefore$ Peak load (P_p) of peak load plant is given by

$P_p = P - P_b$

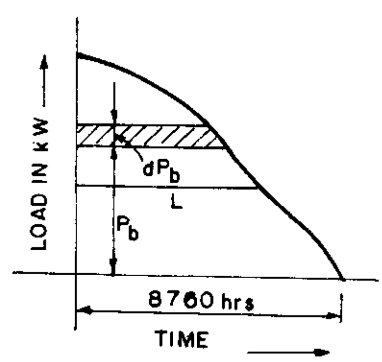


Fig. 35.2.

Number of units generated by peak load plant Q_p is given by

$$Q_p = Q - Q_b$$

$$\therefore \quad C_1 = A_1P_b + B_1Q_b.$$

$$C_2 = A_2(P - P_b) + B_2(Q - Q_b).$$

The total cost of the system C is given by

$$C = C_1 + C_2 = (A_1P_b + B_1Q_b) + [A_2(P - P_b) + B_2\,(Q - Q_b)]$$

The required condition for the minimum value of C is

$$\frac{dC}{dP_b} = 0.$$

$$\therefore \quad (A_1 - A_2) + (B_1 - B_2)\frac{dQ_b}{dP_b} = 0.$$

$$\therefore \quad \frac{dQ_b}{dP_b} = \frac{(A_1 - A_2)}{(B_2 - B_1)} \text{ hrs as } \frac{\text{kWh}}{\text{kW}} = \text{hours.}$$

Thus for economic load sharing, the area under the load duration curve is so divided by horizontal line that its magnitude is given by

$$L = \frac{A_1 - A_2}{B_2 - B_1} \text{ hrs.} \quad ...(a)$$

This indicates that for economic load sharing, peak load station will work for L hours per year.

The value of L should be always positive

$\therefore$ $A_1 > A_2$ and $B_2 > B_1$ or $B_1 < B_2$

A_1 is higher and B_1 is lower for base load plant compared with respective values of peak load plant.

After finding the value of L in hrs, we can mark the point d as $\frac{L}{8760} \times 100$ (percentage time) is known. Draw the vertical line through d which cuts the load duration curve at point T. Draw the horizontal line TS as shown in Fig. 35.3. Now the area A_p above the line ST gives the energy generated by peak load plant and area below it (A_b) gives the energy generated by the base load plant.

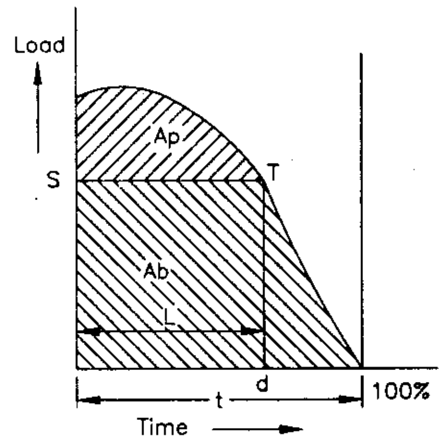


Fig. 35.3.

For drawing the load duration curve, the scale along time axis taken as 1 cm = x%, and along load axis, 1 cm = y in kW

$$\therefore \quad 1 \text{ cm}^2 = (x\%) \times y$$

But

$$100\% = 8760 \text{ hrs.}$$

$$\therefore \quad 1 \text{ cm}^2 = \left(\frac{x}{100} \times 8760\right) \times y \text{ in kWh.}$$

If areas A_b and A_p in cm^2 are known, then,

$$Q_b = A_b \times \left(\frac{x}{100} \times 8760\right) \times y \text{ in kWh} \quad ...(b)$$

(energy generated by base load plant)

$$Q_p = A_p \times \left(\frac{x}{100} \times 8760\right) \times y \text{ in kWh} \quad ...(c)$$

(energy generated by peak load plant)

Note :—If the cost structure for the two stations is given as

$C_1 = A_1.\text{kW} + B_1.\text{kWh} + D_1$

and $C_2 = A_2.\text{kW} + B_2.\text{kWh} + D_2$

Even then the equation (a) is valid. Proof is left as exercise for the students.

Thus the division of load between the two power plants of an interconnected system can be achieved and this results in overall economy of the operation. Under most economical operation of the interconnected system, the energy to be generated by base load plant and by peak load plant is also fixed.

The method described above for distributing the load among the two power plants in an interconnected system can be used for any type of plants as thermal + diesel, thermal + hydro, nuclear + hydro and so on.

35.4. STORAGE TYPE HYDRO-ELECTRIC PLANT IN COMBINATION WITH STEAM PLANT

In thermal power plants, some part should be kept hot to meet sudden fluctuations of peak load which may involve a loss of 1 to 2.5% of full load steam consumption. But hydro-plants can take up the load quick and follow the peak variations much better than thermal plants. Also when the evening loads fall gradually, hydro-plants can meet this requirement and allow the thermal plants to shut down independently of the system requirement.

There is greater reliability in hydro-plants and it is still more in a combined system. In a combined system of hydro and thermal, water storage increases the application of more hydro-power in normal or heavy run-off years, while steam plant can help during the time of draught. The hydro-plant is used as base load when the run-off is sufficient particularly in monsoon period and thermal plant works as peak load plant. The thermal plant is used as base load plant during the draught period and hydro-plant works as peak load plant. Their uses as base load or peak load plant are shown in Fig. 35.4.

Steam stations can be used with an advantage in combination with hydro-plant to obtain economy from the mixed system as initial cost of steam-station is less than hydro-station of the same capacity. Steam stations can be used at any portion of the load duration curve but it is more expensive to use as peakload station at low load factors.

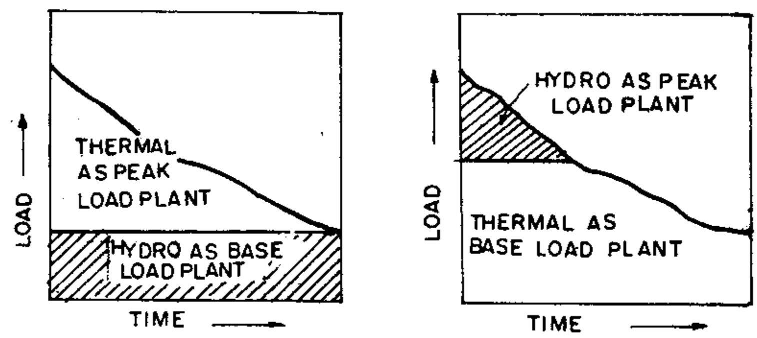


Fig. 35.4. (*a*) Hydro-plant used as base load plant during normal run-off in an interconnected system.

Fig. 35.4 (*b*) Hydro-plant used as peak load plant during draught period in an interconnected system.

The economic factors considered for the following combined systems are :

(I) The bulk of power generation is hydro and fuel has to be imported or hauled from long distances for supplementing thermal power as in Norway, Sweden, Switzerland, Italy, and some parts of India.

(II) The bulk of power generation is thermal due to non-availability of hydro-potential and the existing hydro-power is used to supplement the thermal as in Britain and some parts of India.

(III) Both resources are available in U.S.A., U.S.S.R., France, Germany and India.

Case I. Predominant Hydro. Some of hydro-plants are used as base load plants (as run-off river plants) and some are used as peak load plants. The periods of maximum demand may not coincide with periods of maximum run-off, as in countries where the water is drawn from melting snow and maximum run-off is available in early summer when power demand is less and there is shortage of water in winter as rivers are frozen. When the hydro-plants carry the major demand throughout the year then the thermal plants are used in a combined system to cover the hydro-power efficiency during low run-off periods.

Case II. Predominant Thermal. It is always advantageous to develop hydro-plants to operate even at comparatively low annual load factors. The reason is that the cost of storage of water forms a major portion of the capital investment which is independent of annual load factor and capital cost is less for low than for a high load factor. Therefore, in a predominantly thermal system, it is preferable to develop hydro power at the lowest practical load factor. A further advantage of increased capacity in a low load factor installation is that spillage can be reduced during high run-off period by operating the plant for a longer period thereby economising the use of fuel in thermal stations.

Case III. Hydro and Thermal Equally Predominant. The hydro-power resources can be developed as base load plants (Koyna, Sharavasti and Cauvery). Some tributary streams can also be developed as storage projects to take the peak load. In the combined operation of hydro and thermal plants, the total capacity of hydro-plant which is firm must be considered. The firm capacity of the hydro-plant is also different in summer and winter, therefore, thorough study should be made for all months of the year.

There is optimum ratio of hydro power to total peak demand which gives minimum cost for power supply. This is particularly true for the areas where the cost of hydro-power development is high and fuel cost is low. In areas where fuel is cheap and cost of hydro-power development is not high, the economic power ratio lies between 0.25 to 0.4. In areas where fuel is costly and favourable hydro-power plant sites are abundant, the ratio will be appreciably higher (0.8 – 0.9).

The economic balance between hydro and steam power in an interconnected system at any time depends upon the nature of load curve, run-off and its seasonal variation, cost of fuel, availability of condensing water and many others.

Some of the basic factors for combining the hydro and thermal stations are discussed here.

1. Fuel Consumption. The thermal plant at no load requires 7% of full load consumption of fuel. It is always necessary to keep few parts of the plant always hot even not working when the plant is used as peak load plant. Therefore, thermal plants run more economically as base load plants than peak load plants.

2. Grouping of Thermal Plants in Combined System. It is always necessary that the plant working at the lowest cost per kW-hr generated should take the lowest position in the annual load duration curve and the machines should be arranged in ascending order of their unit fuel cost within that curve to reduce the overall fuel consumption and overall generating cost. Therefore, the oldest and low efficiency thermal stations are arranged in the load duration curve to take the peak loads. A new base load steam station would occupy the lowest position in the load duration curve and all other stations will move further up the curve and each plant will generate less energy (kW-hr). The average full consumption of thermal plants in the load curve will be reduced due to low specific fuel consumption of new plant which generates maximum kW-hr and less economical plant will generate less kW-hr.

3. Introduction of Hydro-plant into a Predominantly Thermal System. The introduction of hydro-plant in an interconnected system has important effects on the total fuel consumption of the system and overall generating cost. Few of them are listed below :

(*a*) Fuel required to keep the boilers hot to take the peak load is saved.

(*b*) The quantity of operation of peak region is improved because the hydro-plant can follow more closely and rapidly the variation in demand.

(*c*) The operation of hydro-plant as peak load-plant even at 15% annual load factor is economical than thermal plant.

4. Installed Capacity of Hydro and Thermal Plant. The minimum total installed capacity of hydro and thermal plants must be equal to the peak load required with adequate allowance for spare plant. If the maximum continuous rating is taken as firm capacity then 10% extra is taken as spare capacity in case of thermal plant. The percentage spare in case of hydro-plant is less than thermal plant due to its higher reliability. With interconnected system, the spare capacity required lies between 5 to 10% of firm hydro-power capacity and is considered adequate.

The most economical combination of hydro and thermal plants can be found out from input-output curves to meet the various load demands. A proper load dispatching programme can be worked out if the data of the plants and capacities of interconnecting transmission lines are available in hand.

In India, such systems are adopted in Bombay and Madras areas. The typical examples of interconnected systems in India are Tata Power Systems (770 MW hydro + 370 MW thermal), Damodar Valley Grid (140 MW hydro + 150 MW thermal), Madras Electricity System (626 MW hydro + 278 MW thermal) and Andhra Pradesh Power System (550 MW hydro + 242 MW thermal). The figures given are based on the data published in the year 1963.

The interconnection of hydro and thermal plants is being adopted all over the world. This is especially useful for developing countries like India where economy is desirable at every stage of development.

35.5. RUN-OF-RIVER PLANT IN COMBINATION WITH STEAM PLANT

The quantity of water available is not steady throughout the year in case of run-of-river plants. Therefore, it is not possible to use the run-of-river plant to supply the variable load. The variation of run-off during the year does not match the variation of power demand (load) during the year. Therefore, it is necessary to combine such hydro-plant with steam plant to supply the load according to requirement with maximum reliability.

The run-of-river plant can be used as base load plant during rainy season and thermal plant is used to take peak load. During dry season ; the thermal station can be used as base load plant and run-of-river plant is used to take peak load.

The procedure used in adopting a run-of-river plant is combination with steam plant is given below :

1. Plot the load duration curve of the system to be supplied. Find out the load factor and also the average load.

2. Plot the power available with the run-of-river plant for the same duration. This represents the power available curve.

3. The average power calculated from the load curve known as prime rate of power must be supplied by the combination of steam and hydro-stations. This is also known as *'prime-hydro-steam rate'*.

4. From the power curve, find out a minimum power which can be supplied with hydro-station. It is general practice to take the minimum power available for 97% of the time from the power duration curve as the minimum hydro-power-rate.

5. Find out the maximum steam power rate. This is the power rate to be supplied by the steam station when the hydro-station is supplying power at the minimum hydro-power-rate.

∴ Max. steam power rate = (Prime hydro-steam-power rate) – (Minimum hydro-power-rate)

Then find the ratio x defined as

$$x = \frac{\text{Minimum hydro-power rate}}{\text{Prime hydro-steam rate}}$$

6. From the load duration curve, we can find out the total energy required during the year and prime-hydro-steam rate is also known.

If the run-of-river plant is used as perk load plant during the period of minimum flow, it will supply the energy for a shorter period and this energy will be at the top of the area under the load curve. The energy supplied by the hydro-plant is x-times the total energy supplied. Now draw the line of demarcation as shown in Fig. 35.5 dividing the area into two parts. The capacity of hydro-plant required is from the highest part of the load curve to the demarcation line. The remaining load is to be supplied by the steam station.

In a combined system, it is always desirable to use the hydro-plant to the best extent possible when enough water is available and therefore it is desirable to allow the run-of river plant to take the base load during rainy season. Its economical justification over the thermal plant when working alone to take the required load is only possible after complete economical analysis.

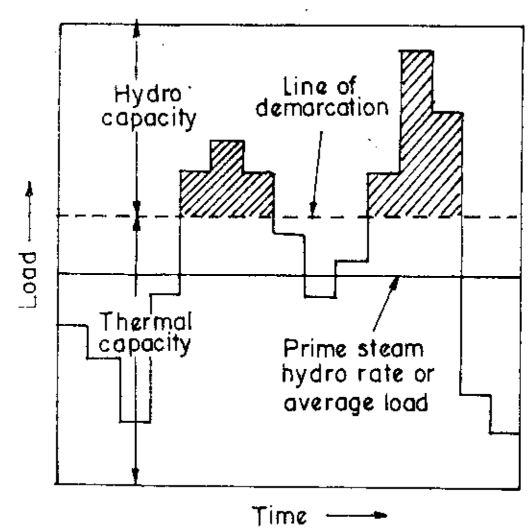


Fig. 35.5. Load curve of combined run-of-river and thermal station when the run-of-river plant is used as peak load plant.

35.6. PUMP STORAGE PLANT IN COMBINATION WITH STEAM OR NUCLEAR POWER PLANT

The old and inefficient steam stations are generally used to take peak loads whenever available. In the absence of suitable plants to take load, it is desirable to develop pumped storage plant for the purpose. The pumped storage plant is useful in an interconnected system to supply sudden peak loads of short duration—a few hours in the years.

The advantages of pump-storage plant in an interconnected system are listed below :

1. It permits more economical loading of thermal plants.
2. It minimises wastage of off-peak energy of thermal plants.
3. It stores the energy using off-peak energy of thermal plant and the same is supplied during demand.

British Electricity Generating Board has put into operation a Festioniog mixed pump storage plant of 300 MW with nuclear power station of 500 MW capacity at Trawinydd. This arrangement has increased the capacity factor and reduced the cost of generation at nuclear station. A similar arrangement is proposed at Ramganga power station in U.P. Existing site of Ramganga can be economically developed for mixed pump storage scheme in conjunction with nuclear power station. A parallel development of nuclear power station of 400 MW capacity near the hydro-site could provide cheap pumping energy to the pump storage plant during off-peak hours. This arrangement will enable the nuclear station to operate at high capacity factor and thereby make it competitive as compared to conventional thermal station in that region where the coal prices are relatively high. Proposed mixed scheme at Ramganga will be relatively much lower in capital cost per kW than Ffestioniog scheme because of favourable site conditions and availability of suitable reversible generating units which were not fully developed at the time of construction of Festioniog scheme. This proposed mixed scheme will be highly economical for power generation purposes.

35.7. CO-ORDINATION OF HYDRO-ELECTRIC AND GAS TURBINE STATIONS

The gas turbine plants as peak load plants are most economical when the amount of energy supplied at peak load is small part of the load energy supplied and the total factor is less than 15%.

The common capacity of the gas turbine plant varies from 10 MW to 25 MW. The capital cost of the gas turbine plant is considerably less (Rs. 1000 to 12000/kW) compared with steam plant (Rs. 16000 to 20000/kW). The thermal efficiency of gas turbine plant (25%) is less than steam plant (36%). The high working cost of gas turbine plant is compensated by lower fixed charges and lower operating and maintenance charges.

The gas turbine plant has number of advantages over steam plant when used as peak load plant. Few of them are listed below :

(1) The space required for gas turbine plant is less than steam plant of the same capacity.

(2) The number of operators required is less.

(3) The response of gas turbine plant is quick.

(4) The quantity of cooling water required is very less compared with steam plant.

(5) It does not require heavy foundations.

(6) The construction and installation period required is considerably less.

Gas turbine plants as peak load plants are considered only in countries where the cost of gas and oil is low.

35.8. CO-ORDINATION OF HYDRO-ELECTRIC AND NUCLEAR POWER STATION

When the nuclear stations are used in co-ordination with hydro-stations, they are used on base load (90% load factor and above) as close and quick regulation of nuclear power station under variable load operation is difficult for the reasons mentioned earlier.

The nuclear power plant unit size is large (not less than 150 MW) for economic reasons. Therefore, system should have loads large enough to justify the large capacity of nuclear power station.

First, annual load duration curve is drawn and the nuclear station is adjusted on the base load portion of the diagram. The procedure for finding out the most economical loading given in article 35.3 can be used for this combination as desirable load factor of the nuclear plant is high and its capacity is also high.

35.9. CO-ORDINATION OF DIFFERENT TYPES OF POWER PLANTS

When different power plants are available in a particular region, and working in parallel, it is necessary to coordinate them and use the plants with maximum economy or with minimum generation cost. The coordination is necessary in achieving the most economical operation of the existing plants. The type of plants used in practice are basically hydro, thermal, nuclear, gas turbine and diesel plants.

The problem of the co-ordination of different types of power stations for the best possible working and economy is extremely complicated as the factors considered for economical co-ordination are large in number. The initial capital cost, fuel cost, operation and maintenance cost, availability of fuel, the economics of base load and peak load operation, the working characteristics of the plants, transmission liability and cost of incremental power are some of the factors to be considered for economic loading of power stations in an interconnected system. Many times, the best co-ordination depends on the nature of load duration curve and availability of fuels and resources in the country.

The desirable inclusion of different types of power plants in annual load curve is shown in Fig. 35.6. The local conditions may change the sequence as per the availability of fuels and resources.

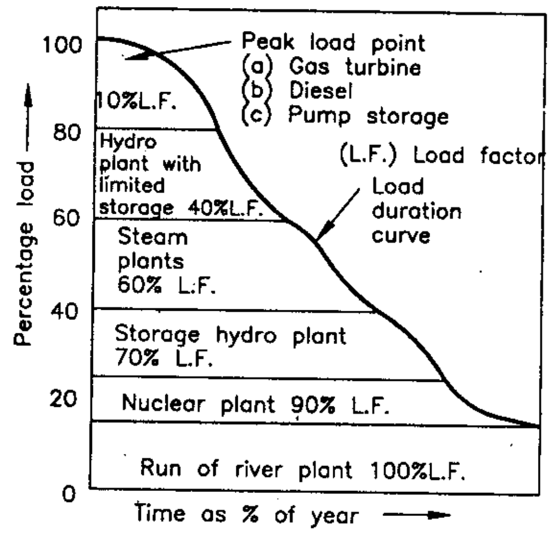


Fig. 35.6. Annual load duration curve showing loads allocated to different plants.

SOLVED PROBLEMS

Problem 35.1. *A load duration curve of a system is a straight line, the maximum and minimum loads being 100 MW and 20 MW respectively. The load is supplied by base load and peak load plants. The costs of both are given as :*

For base load plant : Rs. 200/kW-year + 5 P./kWh.

For peak load plant : Rs. 50/kW-year + 10 P./kWh.

For minimum overall cost, determine the load shared by peak load plant and annual load factors for both stations.

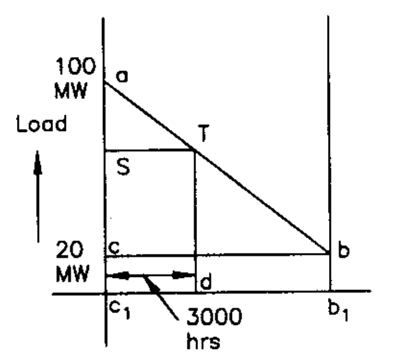


Fig. Prob. 35.1.

Solution.

(*a*) The given data is :

$$A_1 = 200,\ B_1 = 0.05,\ A_2 = 50,\ B_2 = 0.1$$

The time, L hrs for which base load to be operated for minimum overall cost is given by :

$$L = \frac{A_1 - A_2}{B_2 - B_1} = \frac{200 - 50}{0.1 - 0.05} = 3000 \text{ hrs.}$$

If P_b is peak load on the base load plant then P_b(peak load on the peak plant) = $100 - P_b$

Now from the triangles *abc* and *aTS*

$$\frac{100 - P_b}{100 - 20} = \frac{3000}{8760}$$

$$\therefore \quad P_b = 70.6 \text{ MW}$$

$$\therefore \quad P_b = 100 - 70.6 = 29.4 \text{ MW.}$$

(*b*)
$$\text{L.F. (base load)} = \frac{\text{Average load}}{\text{Peak load}} \times \frac{8760}{8760} = \frac{\text{Area 'ST } bb_1\ C_1\ S\text{'}}{P_b \times 8760}$$

$$= \frac{\text{Area } 'ST\ bcS' + \text{Area } 'bb_1\ c_1\ cb'}{P_b \times 8760}$$

$$= \frac{\frac{1}{2}(1000 + 8760) \times (70.6 - 20) + 8760 \times 20}{29.4 \times 8760} = 0.68 = \mathbf{68\%}.$$

L.F. (peak load plant) $= \frac{\text{Area } 'aTSa'}{P_p \times 8760} = \frac{\frac{1}{2} \times 3000 \times 29.4}{29.4 \times 8760} = \mathbf{0.17 = 17\%}.$

Problem 35.2. *The estimated costs of two power stations I and II running parallel are Rs. (2500 kW + 0.550 kWh) and Rs. (2400 kW + 0.6 kWh) respectively and supply to a system whose maximum load is 100 MW and minimum load is 10 MW during the year. The load varies as straight line. Find for minimum cost of generation,*

(*a*) *Installed capacity of each station.*

(*b*) *The annual load, capacity and capacity use factor of each station.*

(*c*) *The average cost of production per kWh for entire system. Assume reserve capacity of II is 20%.*

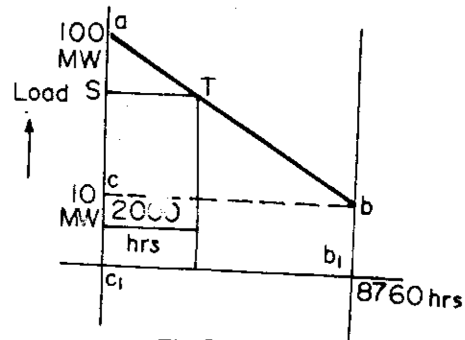


Fig. Prob. 35.2.

Solution.

The given data is : $C_1 = 2500 \text{ kW} + 0.550 \text{ kWh}$

$C_2 = 2400 \text{ kW} + 0.6 \text{ kWh}.$

$A_1 = 2500,\ A_2 = 2400$

$B_1 = 0.55,\ B_2 = 0.6$

$$L = \frac{A_1 - A_2}{B_2 - B_1} = \frac{2500 - 2400}{0.6 - 0.55} = 2000 \text{ hrs.}$$

Again from the triangles *abc* and *aTS*

$$\frac{100 - P_b}{100 - 10} = \frac{2000}{8760}$$

$\therefore \quad P_b = 80 \text{ MW}$

$\therefore \quad P_p = 100 - 80 = \mathbf{20\ MW}$

(*a*) Installed capacity of base load plant

$P_b = \mathbf{80\ MW}$

Installed capacity of peak load plant

$= 20 \times 1.2 = \mathbf{24\ MW}$ (as reserve capacity 20% is given)

(*b*) **For base load plant**

$$\text{L.F.} = \frac{\text{Actual units generated}}{P_b \times 8760} = \frac{\frac{1}{2}(2000 + 8760) \times (80 - 10) + 10 \times 8760}{80 \times 8760}$$

(from Fig. Prob. 35.2)

$= 0.65 = \mathbf{65\%}.$

C.F. = L.F. = 0.65 (as there is no reserve capacity)

$$\text{Use factor (U.F.)} = \frac{\text{C.F.}}{\text{L.F.}} = \frac{0.65}{0.65} = 1$$

For peak load plant

$$\text{L.F.} = \frac{\text{Actual units generated}}{P_b \times 8760} = \frac{\frac{1}{2} \times 2000 \times (100 - 80)}{20 \times 8760} = 0.115 = \mathbf{11.5\%}.$$

$$\text{C.F.} = \frac{\text{Average load}}{\text{Actual plant capacity}}$$

$$= \frac{\text{Actual units generated}}{24 \times 8760} = \frac{\frac{1}{2} \times 2000 \times (100 - 80)}{24 \times 8760} = 0.095 = \mathbf{9.5\%}$$

$$\text{U.F.} = \frac{\text{C.F.}}{\text{L.F.}} = \frac{0.095}{0.115} = 0.825 = \mathbf{82.5\%}.$$

(*c*) **For I plant (base)**

Total units generated $= \frac{1}{2}(2000 + 8760) \times (80 - 10) + 10 \times 8760$

$= 464200 \text{ MWh} = \mathbf{464.2 \times 10^6 \text{ kWh.}}$

$C_1 = 80 \times 10^3 \times 2500 + 464.2 \times 10^6 \times 0.55$

$= 200 \times 10^6 + 255.3 \times 10^6 = \mathbf{455.3 \times 10^6 \text{ rupees}}$

For II plant (peak)

Total units generated $= \frac{1}{2} \times 2000 \times (100 - 80) = 20000 \text{ MWh} = 20 \times 10^6 \text{ kWh.}$

$\therefore \quad C_2 = 20 \times 10^3 \times 2400 + 20 \times 10^6 \times 0.6$

$= (48 + 12) \times 10^6 = 60 \times 10^6$

Total generated units from both plants

$= 464.2 \times 10^6 + 20 \times 10^6 = 484.2 \times 10^6 \text{ kWh.}$

Total generating cost (C) $= C_1 + C_2 = 455.3 \times 10^6 + 60 \times 10^6 = 515.3 \times 10^6$ rupees.

$\therefore$ Average cost $= \frac{515.3 \times 10^6}{484.2 \times 10^6} =$ **Rs. 1.065/kWh.**

Problem 35.3. *The annual load duration curve of a station varies uniformly from 64000 kW to zero. The load is supplied by two stations whose cost equations are given as :*

$$C_1 = Rs.\ (840000 + 840\ kW + 0.116\ kWh).$$
$$C_2 = Rs.\ (500000 + 440\ kW + 0.2985\ kWh).$$

Find the minimum cost of generation in Rs./kWh for the system.

Solution.

$$L = \frac{A_1 - A_2}{B_2 - B_1} = \frac{840 - 440}{0.2985 - 0.116} = 2190 \text{ hrs.}$$

From the triangles aTS and abo, we get

$$\frac{64000}{8760} = \frac{P_p}{2190}$$

$\therefore \quad P_p = \frac{64000}{8760} \times 2190 = 16000 \text{ kW.}$

$\therefore \quad P_b = 64000 - 16000 = 48000 \text{ kW.}$

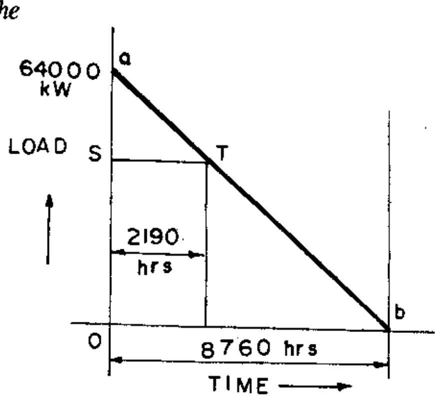


Fig. Prob. 35.3.

The kWh generated by base load plant

$= \frac{1}{2}(8760 + 2190) \times 48000 = 2628 \times 10^5 \text{ kWh.}$

The kWh generated by peak load plant

$= \frac{1}{2} \times 2190 \times 16000 = 175.2 \times 10^5 \text{ kWh.}$

$\therefore$ Total energy generated $= 2628 \times 10^5 + 175.2 \times 10^5 = 2803.2 \times 10^5 \text{ kWh.}$

$C_1 = 840000 + 840 \times 48000 + 0.116 \times 2628 \times 10^5$

$= (84 + 403.2 + 304.9) \times 10^5 = 792.1 \times 10^5$

$C_2 = 500000 + 440 \times 16000 + 0.2985 \times 175.2 \times 10^5$

$= (5 + 70.4 + 52.3) \times 10^5 = 127.7 \times 10^5$

Total cost $C = C_1 + C_2 = 792.1 \times 10^5 + 127.7 \times 10^5 =$ Rs. 919.8×10^5

$\therefore$ Generating cost $= \dfrac{919.8 \times 10^5}{2803.2 \times 10^5} \simeq$ **Rs. 0.33/kWh.**

Problem 35.4. *An estimated total annual operating costs for two proposed station are given by the following expression :*

Station A Rs. $(100 \times 10^4 + 600\ kW + 0.1\ kWh)$

Station B Rs. $(60 \times 10^4 + 350\ kW + 0.2\ kWh)$

where kW represents the station capacity and kWh is the total energy output per year.

The stations are to be used to supply the load having load during curve as shown in Fig. Prob. 35.4 (a). Which station should be used to supply the peak load ? What should be its installed capacity and for how many hours per year should it be in operation to give the minimum total cost per unit generated ?

Solution. Consider station A is more economical and then we will find its generating cost and check it whether it gives lower cost than station B.

Let total cost of generation for station A is C and assume its capacity i.. x (kW). If the total load demand is P kW, then the capacity of station B should be $(P - x)$ kW as shown in Fig. Prob. 35.4 (b).

Let total units generated are S_t and out of this units generated by station A are S_a. Therefore, the units generated by station $B = (S_t - S_a)$.

The total cost of generation is given by

$$C = [100 \times 10^4 + 600\,x + 0.1\,S_a] + [60 \times 10^4 + 350\,(P - x) + 0.2\,(S_t - S_a)]$$

For minimum C, the required condition is

$$\frac{dC}{dx} = 0$$

$$600 + 0.1\frac{dS_a}{dx} - 350 - 0.2\frac{dS_a}{dx} = 0$$

where total capacity (P) and total units generated (S_t) are constant

The above equation gives

$$\frac{dS_a}{dx} = \frac{250}{0.1} = 2500$$

$$dS_a = 2500\,dx \quad ...(a)$$

Consider an elementary strip of area dS as shown in Fig. Prob. 35.4 (b), we get

$$dS = H \,.\, dx \quad ...(b)$$

From equations (a) and (b), we get

$$H = 2500 \text{ hrs.}$$

From similar triangles oab and dcb

$$\frac{ob}{db} = \frac{8760}{H} \text{ where } ob = P = 50000 \text{ kW}$$

Installed capacity for station $B = (P - x)$

$$(P - x) = db = \frac{H}{8760} \times ob = \frac{2500}{8760} \times 50{,}000 = \mathbf{14275\ kW}$$

$\therefore$ Units generated by station B

$$= S_t - S_a = \text{Area of } bdc$$

$$= \frac{1}{2} \times db \times H = \frac{1}{2} \times 14275 \times 2500 = \mathbf{178 \times 10^5\ kWh}$$

Total units generated S_t

$= \text{Area of } boa$

$= \frac{1}{2} \times ob \times oa = \frac{1}{2} \times 50{,}000 \times 8760 = \mathbf{2190 \times 10^5 \text{ kWh}}$

Units generated by station A

= Total units generated – Units generated by station B

$= 2190 \times 10^5 - 178 \times 10^5 = 2012 \times 10^5$ units

$$S_a = \frac{1}{2}(2500 + 8760) \times (50{,}000 - 14275) = 2012 \times 10^5 \text{ kWh}$$

Capacity of station A

$= 50{,}000 - 14275 = \mathbf{35725 \text{ kW}}$ and units generated are $\mathbf{2012 \times 10^5 \text{ kWh}}$

C = Total cost of A + Total cost of B

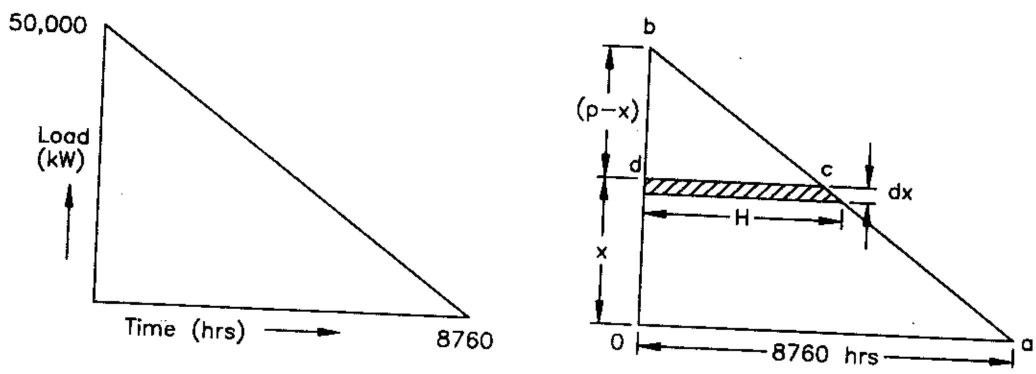
$= [100 \times 10^4 + 600 \times 35725 + 0.1 \times 2012 \times 10^5] + [60 \times 10^4 + 350 \times 14275 + 0.2 \times 178 \times 10^5]$

$= 10^5 [(10 + 214.35 + 201.2) + (6 + 49.9625 + 35.6)]$

$= 10^5 [425.55 + 91.563] = \mathbf{517.113 \times 10^5}$

Overall cost of generation

$= \frac{517.113 \times 10^5}{2190 \times 10^5} = \text{Rs. } 0.236 = \mathbf{23.6 \text{ paise/kWh}}$



(a) (b)

Fig. Prob. 35.4.

Problem 35.5. *Load duration curve data of a particular system is listed below :*

Percentage Time of a year	*0*	*10*	*20*	*30*	*40*	*50*	*60*	*70*	*80*	*90*	*100*
Load in MW	*36.0*	*33.2*	*33*	*29.8*	*29.6*	*29.2*	*28.5*	*28.0*	*22.0*	*12.0*	*8.0*

A base load station has 32 MW capacity and peak load station has 7 MW capacity. The cost structure on yearly basis is given as :

for base load plant—Rs. (48/kW + 0.03/kWh)

for peak load plant—Rs. (36/kW + 0.035/kWh).

Determine the loads on each plant if the system load is taken by both plants running in parallel for least annual cost. Also find the load factor, capacity factor and use factor for both plants.

Solution. The load duration curve is shown in Fig. Prob 35.5 from the given data :

$$L = \frac{A_1 - A_2}{B_2 - B_1} = \frac{48 - 36}{0.035 - 0.030} = 2400 \text{ hrs.}$$

$$= \frac{2400}{8760} \times 100 = 27.2\% \text{ of year}$$

The scale used for % time along X-axis is 1 cm, = 20% time and for load along Y-axis is 1 cm = 10 MW.

Mark the point along time axis for 27.2% time and draw a vertical line which cuts the load duration curve at point T. Draw horizontal line through T which cuts load axis at S. Read the value.

$\therefore \quad P_b = 30$ MW.

$\therefore \quad P_p = 36 - 30 = 6$ MW as maximum load of the system is 36 MW.

Installed base load and peak load capacity are 32 MW and 7 MW which are higher than required. Therefore, they provide the reserve capacities.

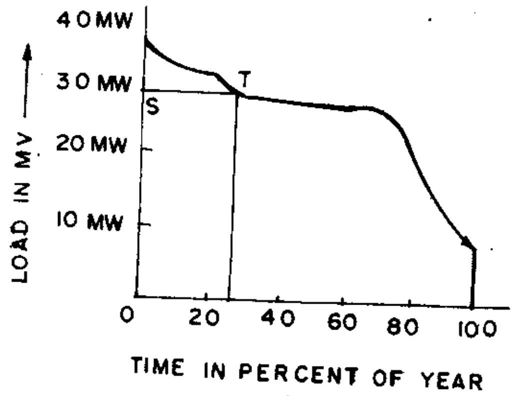


Fig. Prob. 35.5.

Area under the line ST gives the energy generated by base load plant and area above the line ST gives the energy generated by peak load plant. The areas are measured by planimeter

as $\quad A_b = 12.38 \text{ cm}^2$ and $A_p = 0.38 \text{ cm}^2$

(*a*) $\therefore$ *Energy generated by base load plant

$$(Q_b) = A_b\left(\frac{x}{100} \times 8760\right) \times y$$

In this example $\quad x = 20\%, \quad y = 10$ MW

$$Q_b = 12.38 \times \left(\frac{20}{100} \times 8760\right) 10 \times 10^3 = \mathbf{21.4 \times 10^6 \text{ kWh.}}$$

$$\text{L.F.} = \frac{21.4 \times 10^6}{30 \times 10^3 \times 8760} = 0.867 = \mathbf{86.7\%.}$$

$$\text{C.F.} = \frac{21.4 \times 10^6}{32 \times 10^3 \times 8760} = 0.81 = \mathbf{81\%.}$$

$$\text{U.F.} = \frac{\text{C.F.}}{\text{L.F.}} = \frac{0.81}{0.867} = 0.932 = \mathbf{93.2\%.}$$

(*b*) For peak load plant

$$Q_p = 0.38 \times \left(\frac{20}{100} \times 8760\right) \times 10 \times 10^3 = \mathbf{0.662 \times 10^6 \text{ kWh.}}$$

$$\text{L.F.} = \frac{0.662 \times 10^6}{6 \times 10^3 \times 8760} = 0.0127 = \mathbf{1.27\%.}$$

$$\text{C.F.} = \frac{0.662 \times 10^6}{7 \times 10^3 \times 8760} = 0.01085 = \mathbf{1.085\%.}$$

$$\text{U.F.} = \frac{\text{C.F.}}{\text{L.F.}} = \frac{0.01085}{0.0127} = \mathbf{0.855 = 85.5\%.}$$

Problem 35.6. *The maximum and minimum demands of an Industry are 50 MW and 10 MW respectively and these vary linearly. The hydro power plant can take the load of 60 MWh per day of the factory at the time of minimum regulated flow and the remaining is supplied by the thermal plant. It is proposed to pump the water from tail race of the existing plant to reservoir during off-peak period of thermal plant and allowing*

**For the formula used, see the equation (b).*

the thermal plant to run always at full load condition to economise the supply of power. If the overall efficiency of conversion of steam off-peak power to hydel potential power and then hydel power to electric power is 60%, calculate the capacity of steam and hydel plants considering the pumping of water during off-peak period of steam plant.

Solution. The load duration curve is shown in Fig. 35.5.

The maximum supply is 50 MW. Assume that the load taken by existing hydel plant and pump-storage plant is (y) MW then the power supplied by thermal plant will be ($50 - y$) MW.

The off-peak power of the thermal plant represented by the area EFBE can be used for pumping the water. The power supplied by the existing hydel plant will be given by the area CHGC.

Hydel potential in electrical form supplied by pump-storage plant must be equal to the area DEGHD.

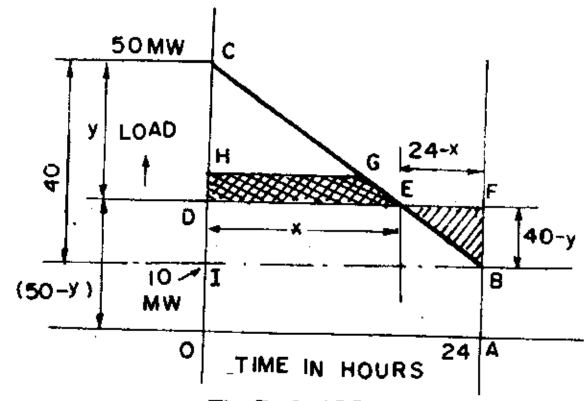


Fig. Prob. 35.5.

∴ Area DEGHD = 0.6 × Area EFBE (as per data given in problem).

∵ Area CEDC – Area CGHC = 0.6 × Area EFBE

But Area CGHC represents the energy supplied by the existing hydel plant which is given as 60 MWh.

Assume x-hours out of 24 hrs, the steam plant operates at full load condition, therefore it operates only ($24-x$) hrs under off-peak condition.

$$\therefore \quad \frac{1}{2}xy - 60 \times 1000 = \frac{1}{2}(24 - x)(40{,}000 - y) \times 0.6.$$

$$xy - 120 \times 10^3 = (24 - x)(40 \times 10^3 - y) \times 1.2 \qquad ...(a)$$

Now from the triangles CDE and CIB, we can write

$$\frac{y}{40000} = \frac{x}{24} \qquad \therefore\ y = \frac{40000}{24}x \qquad ...(b)$$

Substituting the value of y from equation b to equation a and simplifying, we get

$$x^2 + 72x - 1044 = 0$$

$$\therefore \quad x = \frac{-72 \pm \sqrt{5184 + 4176}}{2} = \frac{-72 \pm 96.75}{2}$$

$$\therefore \quad x = \mathbf{12.375\ hrs.}$$

∴ y (total capacity of hydel plant)

$$= \frac{40000}{24} \times 12.375 \times \frac{1}{1000} = \mathbf{20.625\ MW.}$$

∴ Capacity of steam plant

$$= 50 - 20.625 = \mathbf{29.375\ MW.}$$

EXERCISES

35.1. What are the advantages of combinedly operating the power plants in electric power system ?

35.2. Explain the method of determining the distribution of the given load among the two plants for most economic generation.

35.3. Discuss the working of hydro-electric plants having ample storage with steam power plants.

How would you make an economic analysis of the combined operation of the hydro and steam power plants ?

35.4. Explain the advantages of pump storage plant as peak load plant in an interconnected system. Compare its economics with an old steam plant to be used for peak load operation as an alternative to pump storage plant.

35.5. What are the advantages of gas turbine plant as peak load plant in an inter-connected system ?

35.6. What factors decide the distribution of plants for operation on different portions of the annual load duration curve of a power system ?

35.7. Discuss the suitability of steam power plants to supply the load in case of an interconnected system.

35.8. The annual load duration curve of a group of consumers can be taken as straight line. The peak demand is 6000 kW and the minimum demand is 200 kW. The given load is supplied by the combined power system which consists of two power plants. The operating and investment costs of both plants are given by the following expressions :

C_1 = Rs. [35 kW + 0.2 kWh + 800 × 10^4]

C_2 = Rs. [60 kW + 0.19 kWh + 900 × 10^4]

Which station should be used as base load plant and why ? Find the capacity of the base load plant and number of hours operated during the year if the distribution of load is done to give the minimum cost of generation. Also find the unit cost of generation when both plants are used.

35.9. The cost structure of the two plants which are supplying power to a common main in parallel is given as

$C_1 = A_1 + A_2 \cdot \text{kW} + A_3 \cdot \text{kWh}$

$C_2 = B_1 + B_2 \cdot \text{kW} + B_3 \cdot \text{kWh}$

Prove that the condition for most economic loading of the plant is given by

$$h \text{ (hours of loading the base load plant)} = \frac{A_2 - B_2}{A_3 - B_3}$$

35.10. An annual load duration curve of a system of loads is a straight line with maximum of 12 MW at the beginning and 2 MW at the end of the year. Annual costs of base and peak load stations are given below

C_1 = 800000 + Rs. 7500/kW + Rs. 3/kWh (base load)

C_2 = 600000 + Rs. 5500/kW + Rs. 4/kWh (peak load)

Determine the duration of time when peak load station will work in order to obtain the minimum annual cost. Also find the lowest overall cost per kWh in paise.

35.11. The annual load duration curve of a system is a straight line with a maximum demand of 45 MW tapering to zero. The load is to be taken from two sources whose annual cost equations are given below.

C_1 = Rs. (10000 × 10^4 + 657 × kW + Rs. 1.2 × kWh)

C_2 = Rs. (6000 × 10^4 + 365 × kW + Rs. 2 × kWh)

Find the installed capacity and service hours for each station per year to give minimum cost per unit and cost per unit.

35.12. The estimated costs of two power stations in Rs. are given as follows :

C_1 = 12500 kW + 2.75 kWh

C_2 = 12000 kW + 3 kWh

These two stations operate in parallel and supply a load having annual load duration curve as straight line joining two points 0-hours – 100 MW and 8760 hrs – 10 MW. Find (*a*) minimum cost of generation (*b*) installed capacity of each station (*c*) annual load factor, capacity factor and use factor for each station. Assume plant-II has 20% reserve.

□□□