Chapter (8)
ECONOMY (General Problem)

The costs of an enterprise are divided into three major groups:

I: CAPITAL COSTS

II: INVESTMENT CHARGES OR FIXED CHARGES

III: ANNUAL OPERATING COSTS

I: CAPITAL COSTS:

Incurred once during the life of the system. They include: purchase, installation and erection of the equipment.

II: INVESTMENT CHARGES OR FIXED CHARGES:

Incurred annually.

الربا/الفائدة ← **1- INTEREST:** رأس المال

If (P) principal or the amount of loan at the beginning of a period (n) years, with an annual interest (i) then the accumulated sum (S):

الفائدة

→ At the end of 1st year

$$S_1 = P + iP = P(1 + i)$$

→ At the end of 2nd year

$$S_2 = P(1 + i) + iP(1 + i) = P(1 + i)^2$$

➔ And the value at the end of the period (n)

$$S = P(1 + i)^n \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

- Often the interest is compounded more than once a year. If (m) is the number of times per year, (i) is still the interest for a full year, then:

$$S = P\left(1 + \frac{i}{m}\right)^m \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.a)$$

- Sometimes, the borrower needs to charge a certain amount (A) at the end of each year. Such that he would have charges all of his merits at the end of the period.

$$A = S\left[\frac{i}{(1+i)^{n}-1}\right] = P\left[\frac{i}{1-(1+i)^{-n}}\right] \text{ .... (2).}$$

Example 1:

If you have lent someone an amount of 500 J.D for 3 years at an interest of 3%, such that he has to pay you (A) J.D at the end of each year. Find the amount of the payment A.

Solution:

P=500 J.D
i=0.03
n=3 years

$$\rightarrow A = 500\left[\frac{0.03}{1-(1+0.03)^{-3}}\right] = 176.765\, J.D$$

In other words:

بدفع 15 زيادة

At the end of 1st year, the amount is: 500 (1+0.03) = 515 J.D

The borrower pays: 176.756 and keeps: 338.235 J.D. بدفع 18 زيادة

At the end of 2nd year, the amount is: 338.295×1.03 = 348.382 J.D

The borrower pays: 176.756 and keeps: 171.617 J.D. بدفع 5 زيادة

At the end of 3rd year, the amount is: 171.617 ×1.03 = 176.765 J.D

2- INVESTMENT:

The owner of a plant can invest the money used for plant construction in some other enterprise and earn from it. It follows that the plant must show prospects of yielding an equivalent return.

3- DEPRECIATION AND AMORTIZATION:

- The factors influencing this are:

عمر المنشأة (المفروض يكون طويل)

A- Life of the Enterprise:

When the demands for the enterprise products vanish, the whole enterprise is curtailed. The equipment may be in a good condition at the moment. If it can be used for other uses. It will be sold as scrap materials and will also incur costs in removing it from the place.

B- Life of the equipment: يقل سعرها أو تتكسر

Equipment deteriorate from corrosion, wear, etc. and often can be repaired. It is difficult to determine the rate of deterioration since the components deteriorate at different rates. The assumed life of equipment must be considered less than the probable life. Some engineers assume that the salvage value just equal the costs of removal.

C- Inadequacy of equipment:

This results when the demand exceeds the equipment capacity. A new equipment may be added to aid in carrying the increased demand.

D- Requirements of public authority:

Restrictions on noise, pollution, safety.

E- Obsolescence of equipment:

When a system of more modern design can operate at a reduction in annual costs, the original system is said to have "obsoleted".

- Depreciation Rate:

It is given by:

$$\frac{A}{S} = \frac{i}{(1+i)^n - 1} \text{.........} \quad (3)$$

Where A is the amount at the end of each year.

➔ Ideally at any instant during the life of a plant (or any enterprise):

رأس المال ← P = Value of plant when sold + Depreciation in funds

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In other words:

The original invested capital = The depreciated value of the plant

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The accumulation in the depreciation

تجمع

- Methods for charging income with amortization of capital funds

1- Straight line method: It is the most common method.

Depreciation rate ←

$$D = \frac{Capital\ Cost - Salvage\ Value}{Life\ of\ Equipment}$$

قيمة الرمي/الزبالة

This amount is deducted form income annually as amortization of capital cost.

2- Percentage method: The method assumes that the value of the capital equipment is decreased by a constant percentage from its value for the previous year. The remaining capital value will reach an estimated salvage.

محاضرة ←

3- Sinking fund method: it is based on investing the amount deducted from income such that it will give the capital value in a period equals the life of the enterprise. Note that the salvage value is considered zero.

تقييم للسعر
كل سنة، بيجي
كل سنة تقييم مختلف
ممكن تزيد أو
تنقص

4- Appraisal method: At the end of each year, an appraisal is made of the value of equipment. The difference in the annual appraisals is considered as the depreciation.

5- Unit method: The amount of capital consumed or depreciated is found by dividing the capital by the number of hours the equipment is capable of working during its life. Each year, this is multiplied by the number of actual working hours.

$$\rightarrow Depriciation\ for\ a\ given\ year = \frac{Capital}{Capability\ in\ hrs} \times Actual\ \ hrs.$$

\- The number of units of production may be used instead of hours.

تغيير الـ Turbines كل 5 سنين يعتبر fixed cost

4- **TAXES:**

There are taxes on the land upon which a plant stands, taxes on equipment, taxes on income.

5- **INSURANCE :**

Insurance against accidents to equipment and persons.

III: ANNUAL OPERATING COSTS

Eliminated in plants that uses renewable resources

1- **FUEL**: Fuel cost varies with the amount of energy produced, plant efficiency, and price of fuel. (It constitutes about 75-85%).

2- **OPERATING LABOUR:** Labour expenses cannot be ignored even in automatic plants and enterprises. In steam plants, labour is required for unloading and storing fuels, disposing of refuse, electrical loading of generators… for plants with a few units, the labour costs are nearly fixed for different ranges of energy production, whereas in plants with a large number of units, less labor is required at part loads. Hydraulic and Gas Turbine plants require less labor than steam plants (because of few equipment) (5-12%)

3- **MAINTENANCE**: Includes the costs of necessary materials and labor (5-20%).

4- **SUPPLIES:** Includes the costs of necessary materials and labour (1-5%).

مهندس حلول مشاكل خط الانتاج / مشرف

5- **SUPERVISOIN:** Consultants, chief engineer, chemist… (1-2%).

6- **OPERATING TAXES**: They depend on the magnitude of output rather than upon the size of the investment. It may be 3-4 times the tax rate applied to capital costs! [0-10%].

بتعتمد عقديش انت بتنتج

*Note the value between brackets indicates the percentage of this cost to total annual operating costs.

METHOD OF ECONOMIC SELECTION

In order to choose a certain category of power generation system (steam, gas turbine, hydraulic, or internal comb, engine) consideration of purchasing the suitable fuel at low prices at the chosen place, the consideration of availability of cooling water, air preheaters, economizers, and other such factors are studied first. Since managers attempt to sell their products at the lowest possible price, otherwise competitors attempt to enter the market at lower prices; a comprehensive study of the annual costs must be made. There are several methods for economy analysis, the "Total annual cost method' is chosen.

cooling towers
are used
if there is
no cooling
water

Total Annual Cost Method:

$$C = C_f + C_O$$

Where:
C_f= Annual fixed cost
C_O =Annual operating cost

- **Annual fixed cost:**

$$C_f = R \times P$$

Where:
P=Principle
R= Fixed charge rate

$$\rightarrow R = \underset{\text{Intrest}}{i} + \frac{i}{(1+i)^n-1} + \overset{\text{taxes}}{t} + \underset{\text{insurane}}{j}$$

$$\rightarrow \text{Depreciation rate} = \frac{i}{(1+i)^n-1}$$

Where:
t = tax
j = Insurance

Now: Investment increases with efficiency which gives lower fuel costs [you pay higher capital (p) for a more efficient system] where as insurance and taxes increase so increasing C_f.

$$\frac{dC}{dp} \; or \; \frac{dC_o}{dp} = \frac{dC_f}{dp}$$

price =

fuel

Energy

Example:

An industrial plant needs 50,000,000 kW-hr of electrical energy a year with maximum demand of 10,000 kW. These can be purchased from the local utility for $480,000 annually. As an alternate scheme the industry considers installing a 10,000 kW steam turbine plant.

Power

The three plants of the following tabulation are proposed:

Boiler

Temp

$\dot{m}$

Boiler

pound per squre inch gage

	Plant A	Plant B	Plant C
Throttle steam conditions : Pressure, psig	200	400	900
Temperature F	550	700	850
Station steam rate (full load) 1b/kW-hr	11.8	10.5	8.5
Average station heat rate. Btu/KW-hr	16,000	13,500	12,000
Unit installation costs			
Steam generators and auxiliaries. ($/1b) –hr capacity	4.08	4.73	6.45
Steam turbine and auxiliaries $ /kw capacity	38	42	51
Electrical equipment ($)	200,000	200,000	200,000
Structures and miscellaneous ($)	200,000	200,000	200,000
Plant operators per shift	4	4	4

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The station will run 24 hr. a day with operators working 8 hr. per day and 5 days a week. Average annual salary for operators $5,200. Repair cost estimated as 90 cents /ton of coal burnt. From past experience, designers see that ultimate installed costs exceed original estimates by 20% General operating supplies are $10.000 annually, Money earn 6% in this business. Plant life 15 years.

Taxes on real estate and property 4%, and the various operating taxes add to 1% of annual operating costs. Annual insurance 0.2% of all equipment costs. Fuel is coal at $ 6.5/short ton with (HHV) of 14.200 Btu/lb.

2000lb ≃ 900kg

Determine which scheme is the economic one.

$1\ L \longrightarrow 0.77\ Kg$

$X\ L \longrightarrow 7.42\ Kg$

L/s fuel

Solution:

- Boiler capacity = station steam rate × station capacity.

Plant A = 11.8 × 10.000 = 120.000 1b/hr.

Plant B = 10.5 × 10,000= 110,000 lb/ hr

Plant C = 8.5 × 10,000 = 90,000 lb/hr

- Installed boiler cost = Boiler, capacity × unit capacity cost

A= 120,000 × 4.08 = $ 490,000

B = 110,000 × 4.73 = $520,000

C = 90,000 × 6.45 = $580,000

- Total investment (boiler + turbine + Electrical + structure) × 1. 20

Plant A = (490,000 +38×10,000 + 200,000+ 200,000) × 1.2 = $1,520,000

Plant B = $ 1, 610,000

Plant C = $ 1,790,000

- Fixed charge rate (R)

$$R = i + \frac{i}{(1+i)^n - 1} + t + j = 0.06 + 0.0431 + 0.04 + 0.002 = 14.5\%$$

- Fuel cost:

Plant A = $\frac{(6.5\ \$ \times 16.000\ Btu/kwh \times 50,000,000\ kW-hr)}{2000 \times 14200\ Btu} = \ \$183,000$

Plant B = $ 155,000

Plant C = $ 138,000

- Operating labor cost:

No of shifts = 7x3=21 shift/week

Each man has to work 5 shifts with 4 men at each shift

- No. of men required = 21/5 x 4 = 17men
- Annual labor cost = 17 × 5200 = $ 88,000

- Annual maintenance costs

Plant A = 0.9 × 183000/6.5 =$25,000

Plant B = $ 21,000

Plant C = $ 19,000

- Annual operating costs = fuel + labor + repair + supplies + operating tax.

Plant A = [183000+ 88,000 + 25000+10000] × 1.01 = $ 309,000

Plant B = $ 277,000

Plant C = 258,000

- Total annual costs = operating costs + Fixed charges at 14.5%

Plant A = 309,000 + 0.1451×1520,000 = $530,000

Plant B = $ 510,000

Plant C = $ 518,000

➔ **With a utility service of $ 480,000, it is noticed that the lowest cost plant (B) can be chosen as the private plant if the public supply cannot be obtained.**

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Economics of Power Generation

9

9.1. Introduction. 9.2. Terms and definitions. 9.3. Principles of power plant design. 9.4. Location of power plant. 9.5. Layout of power plant building. 9.6. Cost analysis. 9.7. Selection of type of generation. 9.8. Selection of power plant equipment—Selection of boilers—Selection of prime movers—Selection of size and number of generating units. **9.9. Economics in plant selection. 9.10. Factors affecting economics of generation and distribution of power. 9.11. How to reduce power generation cost ? 9.12. Power plant—useful life. 9.13. Economics of hydro-electric power plants. 9.14. Economics of combined hydro and steam power plants. 9.15. Performance and operating characteristics of power plants. 9.16. Economic load sharing. 9.17. Tariff for electrical energy**—Introduction—Objectives and requirements of tariff—General tariff form—*Worked Examples—Highlights—Theoretical Questions— Unsolved Examples—Competitive Examinations Questions.*

9.1. INTRODUCTION

In all fields of industry economics plays an important role. In power plant engineering economics of power system use certain well established techniques for choosing the most suitable system. The power plant design must be made on the basis of most economical condition and not on the most efficient condition as the 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 the cost of energy produced to minimum.* Among many factors, the efficiency of the plant is one of the factors that determines the energy cost. In majority of cases, unfortunately, the most thermally efficient plant is not economic one.

9.2. TERMS AND DEFINITIONS

1. Connected load. The connected load on any system, or part of a system, *is the combined continuous rating of all the receiving apparatus on consumers' premises, which is connected to the system, or part of the system, under consideration.*

2. Demand. The demand of an installation or system *is the load that is drawn from the source of supply at the receiving terminals averaged over a suitable and specified interval of time.* Demand is expressed in kilowatts (kW), kilovolt-amperes (kVA), amperes (A), or other suitable units.

3. Maximum demand or Peak load. The maximum demand of an installation or system *is the greatest of all the demands that have occurred during a given period.* It is determined by measurement, according to specifications, over a prescribed interval of time.

4. Demand factor. The demand factor of any system, or part of a system, is *the ratio of maximum demand of the system, a part of the system, to the total connected load of the system, or of the part of the system, under consideration.* Expressing the definition mathematically,

$$\text{Demand factor} = \frac{\text{Maximum demand}}{\text{Connected load}} . \qquad ...(9.1)$$

5. Load factor. The load factor is *the ratio of the average power to the maximum demand.* In each case, the interval of maximum load and the period over which the average is taken should be definitely specified, such as a "half-hour monthly" load factor. The proper interval and period are usually *dependent upon local conditions and upon the purpose for which the load factor is to be used.* Expressing the definition mathematically,

$$\text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}} . \qquad ...(9.2)$$

6. Diversity factor. The diversity factor of any system, or part of a system, *is the ratio of the maximum power demands of the subdivisions of the system, or part of a system, to the maximum demand of the whole system, or part of the system, under consideration, measured at the point of supply*. Expressing the definition mathematically,

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مثلك موصل للبيت 25

$$\text{Diversity factor} = \frac{\text{Sum of individual maximum demands}}{\text{Maximum demand of entire group}} . \qquad ...(9.3)$$

Load factor = 1 for street since all light are lit together

7. Utilization factor. The utilization factor is defined as *the ratio of the maximum generator demand to the generator capacity.*

8. Plant capacity factor. It is defined as the *ratio of actual energy produced in kilowatt hours (kWh) to the maximum possible energy that could have been produced during the same period.* Expressing the definition mathematically,

$$\text{Plant capacity factor} = \frac{E}{C \times t} \qquad ...(9.4)$$

$t' < t$

where, E = Energy produced (kWh) in a given period,
C = Capacity of the plant in kW, and
t = Total number of hours in the given period.

9. Plant use factor. It is defined as *the ratio of energy produced in a given time to the maximum possible energy that could have been produced during the actual number of hours the plant was in operation.* Expressing the definition mathematically,

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$$\text{Plant use factor} = \frac{E}{C \times t'} \qquad ...(9.5)$$

$t'_{max} = t$

where t' = Actual number of hours the plant has been in operation.

10. Types of loads.

(*i*) ***Residential load.*** This type of load includes domestic lights, power needed for domestic appliances such as radios, television, water heaters, refrigerators, electric cookers and small motors for pumping water.

(*ii*) ***Commercial load.*** It includes lighting for shops, advertisements and electrical appliances used in shops and restaurants etc.

(*iii*) ***Industrial load.*** It consists of load demand of various industries.

(*iv*) ***Municipal load.*** It consists of street lighting, power required for water supply and drainage purposes.

(*v*) ***Irrigation load.*** This type of load includes electrical power needed for pumps driven by electric motors to supply water to fields.

(*vi*) ***Traction load.*** It includes trams, cars, trolley, buses and railways.

11. Load curve. A load curve (or load graph) *is a graphic record showing the power demands for every instant during a certain time interval.* Such a record may cover 1 hour, in which case it would be an *hourly load graph* ; 24 hours, in which case it would be a *daily load graph* ; a month in which case it would be a *monthly load graph* ; or a year (8760 hours), in which case it would be a *yearly load graph*. The following points are worth noting :

Refer to Fig. 9.1.

(*i*) *The area under the load curve represents the energy generated in the period considered.*

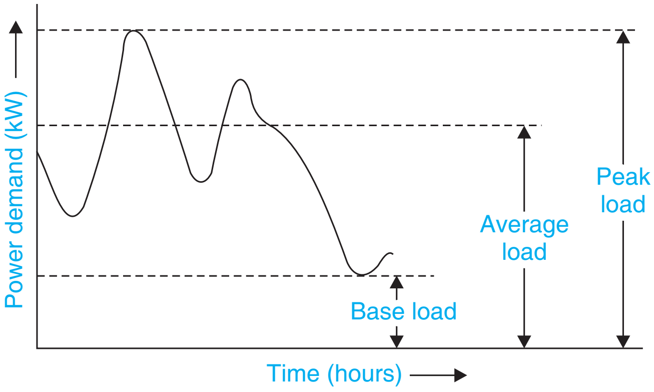

Fig. 9.1. Load curve.

(*ii*) *The area under the curve divided by the total number of hours gives the average load on the power station.*

(*iii*) *The peak load indicated by the load curve/graph represents the maximum demand of the power station.*

Significance of load curves :

- Load curves give full information about the incoming load and help to decide the installed capacity of the power station and to decide the economical sizes of various generating units.
- These curves also help to estimate the generating cost and to decide the operating schedule of the power station *i.e.,* the sequence in which different units should be run.

12. Load duration curve. A load duration curve represents re-arrangements of all the load elements of chronological load curve in order of descending magnitude. This curve is derived from the chronological load curve.

Fig. 9.2 shows a typical daily load curve for a power station. It may be observed that the maximum load on power station is 35 kW from 8 A.M to 2 P.M. This is plotted in Fig. 9.3. Similarly other loads of the load curve are plotted in *descending order* in the same figure. This is called *load duration curve* (Fig. 9.3).

The following points are worth noting :

(*i*) *The area under the load duration curve and the corresponding chronological load curve is equal and represents total energy delivered by the generating station.*

(*ii*) *Load duration curve gives a clear analysis of generating power economically. Proper selection of base load power plants and peak load power plants becomes easier.*

13. Dump power. This term is used in hydroplants and it shows the *power in excess of the load requirements* and it is made available by *surplus water*.

14. Firm power. It is the power which *should always be available even under emergency conditions.*

15. Prime power. It is the power which may be mechanical, hydraulic or thermal that is *always available for conversion into electric power.*

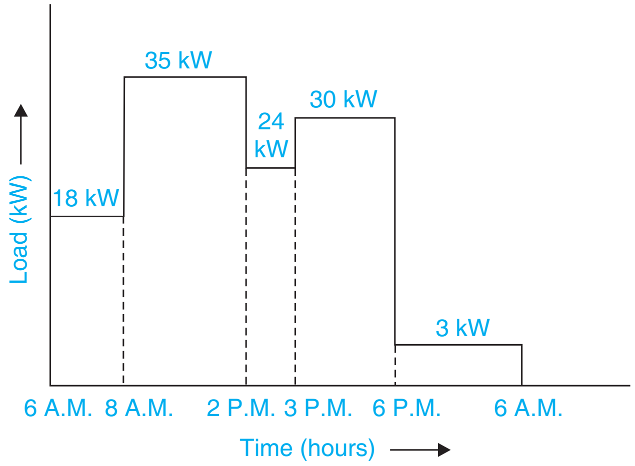

Fig. 9.2. Typical daily load curve.

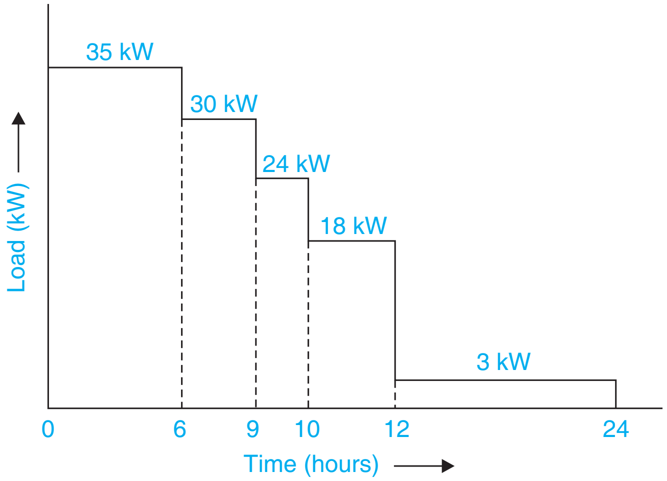

Fig. 9.3. Load duration curve.

16. Cold reserve. It is that *reserve generating capacity which is not in operation but can be made available for service.*

17. Hot reserve. It is that *reserve generating capacity which is in operation but not in service.*

18. Spinning reserve. It is that *reserve generating capacity which is connected to the bus and is ready to take the load.*

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9.3. PRINCIPLES OF POWER PLANT DESIGN

The following *factors* should be considered while designing a power plant :

1. Simplicity of design.
2. Low capital cost.
3. Low cost of energy generated.
4. High efficiency.
5. Low maintenance cost.
6. Low operating cost.
7. Reliability of supplying power.
8. Reserve capacity to meet future power demand.

9.4. LOCATION OF POWER PLANT

Some of the considerations on which the location of a power plant depends are :

1. Centre of electrical load. The plant should be located where there are industries and other important consumption places of electricity. There will be considerable advantage in placing the power station *nearer to the centre of the load.*

- There will be *saving in the cost of copper* used for transmitting electricity as the distance of transmission line is reduced.
- The cross-section of the transmission line directly depends upon the maximum current to be carried. In case of alternating current the voltage to be transmitted can be increased thus reducing the current and hence the *cross-section of the transmission line can be reduced.* This will *save the amount of copper.*
- It is desirable now to have a national grid connecting all power stations. This provides for selecting a site which has other advantages such as nearer to fuel supply, condensing water available.

2. Nearness to the fuel source. The cost of transportation of fuel may be quite high if the distance of location of the power plant is considerable. It may be advisable to locate big thermal power plants at the mouth of the coal mines. Lignite coal mines should have centralised thermal power station located in the mines itself as this type of coal cannot be transported. Such type of power stations could be located near oil fields if oil is to be used as a fuel and near gas wells where natural gas is available in abundance. In any case it has been seen that *it is cheaper to transmit electricity than to transport fuel.* Hence the power plant should be located nearer the fuel supply source.

3. Availability of water. The availability of water is of greater importance than all other factors governing station location. Water is required for a thermal power station using turbines for the following two purposes :

(*i*) To supply the make-up water which should be reasonably pure water.

(*ii*) To cool the exhaust steam. This cooling process is done in case of diesel engines too. For *bigger power stations* the quantity of this cooling water is tremendous and requires *some natural source of water* such as *lake, river or even sea.* Cooling towers could be used economically as the same cooling water could be used again and again. Only a part of make up water for cooling will then be required. For *small plants spray pounds* could sometimes be used. *It is economical to limit the rise in cooling-water temperature to a small value (between 6°C and 12°C), and to gain in cycle efficiency at the expense of increased cooling water pumping requirement.*

4. Type of soil available and land cost. While selecting a site for a power plant it is important to know about the character of the soil. If the soil is loose having low bearing power the pile foundations have to be used. Boring should be made at most of the projected site to have an idea of the character of the various strata as well as of the bearing power of the soil. *The best location is that for which costly and special foundation is not required.*

In case of power plants being situated near metropolitan load centres, the land there will be very costly as compared to the land at a distance from the city.

9.5. LAYOUT OF POWER PLANT BUILDING

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The following points should be taken care of while deciding about power plant building and its layout :

1. The power plant structure should be simple and rugged with pleasing appearance.

2. Costly materials and ornamental work should be avoided.

3. The power plant interior should be clean, airy and attractive.

4. The exterior of the building should be impressive and attractive.

5. Generally the building should be *single storeyed*.

6. The layout of the power plant should first be made on paper, the necessary equipment well arranged and then design the covering structure. In all layout, allowances must be made for sufficient clearances and for walkways. Good clearance should be allowed around generators, boilers, heaters, condensers etc. Walkway clearances around hot objects and rapidly moving machinery should be wider than those just necessary to allow passage. Also the galleries in the neighbourhood of high tension bus bars should be sufficient as the space will permit.

7. Provision for future extension of the building should be made.

8. The height of the building should be sufficient so that overhead cranes could operate well and the overhauling of the turbines etc. is no problem. Sufficient room should be provided to lift the massive parts of the machines.

9. Each wall should receive a symmetrical treatment in window openings etc.

10. The principal materials used for building the power plant building are brick, stone, hollow tiles, concrete and steel.

11. In case of a *steam power plant*, there are distinct parts of the building *viz*., *boiler room, turbine room* and *electrical bays*. Head room required in the boiler room should be greater than in the others. Ventilation in boiler room presents greater difficulty because of heat liberated from the boiler surfaces. The turbine room is actually the show room of the plant. Mezzanine flooring should be used in the power plant. The chimney height should be sufficient so as to release the flue gases sufficiently high so that the atmosphere is not polluted and the nearby buildings are not affected.

12. The foundation of a power plant is one of the most important considerations. For this the bearing capacity of the sub-soil, selection of a working factor of safety and proportioning the wall footings to economical construction should be well thought of and tested. The pile foundations may have to be used where the soils have low bearing values.

13. In any power plant *machine foundation* plays an important part. The machine foundation should be able to distribute the weight of the machine, bed plate and its own weight over a safe subsoil area. It must also provide sufficient mass *to absorb machine vibrations*.

14. Sufficient room for storage of fuel should be provided indoor as well as outdoor so as to ensure against any prolonged breakdown.

9.6. COST ANALYSIS

The cost of a power system depends upon whether :

(*i*) an entirely new power system has to be set up, or

(*ii*) an existing system has to be replaced, or

(*iii*) an extension has to be provided to the existing system. The cost interalia includes :

1. Capital Cost or Fixed Cost. It includes the following :

(*i*) Initial cost	(*ii*) Interest
(*iii*) Depreciation cost	(*iv*) Taxes
(*v*) Insurance.	

2. Operational Cost. It includes the following :

(*i*) Fuel cost	(*ii*) Operating labour cost
(*iii*) Maintenance cost	(*iv*) Supplies
(*v*) Supervision	(*vi*) Operating taxes.

The above mentioned costs are discussed as follows :

(*a*) Initial cost

Some of the several factors on which cost of a generating station or a power plant depends are :

(*i*) Location of the plant.
(*ii*) Time of construction.
(*iii*) Size of units.
(*iv*) Number of main generating units.
(*v*) The type of structure to be used.

The *initial cost* of a power station includes the following :

1. Land cost
2. Building cost
3. Equipment cost
4. Installation cost
5. Overhead charges which will include the transportation cost, stores and storekeeping charges, interest during construction etc.

— To *reduce the cost of building*, it is desirable to eliminate the superstructure over the boiler house and as far as possible on turbine house also.

— The *cost on equipment can be reduced* by adopting unit system where one boiler is used for one turbogenerator. Also by simplifying the piping system and elimination of duplicate system such as steam headers and boiler feed headers. The cost can be further reduced by eliminating duplicate or stand-by auxiliaries.

— When the power plant is not situated in the proximity to the load served, the cost of a primary distribution system will be a part of the initial investment.

(*b*) Interest

All enterprises need investment of money and this money may be obtained as loan, through bonds and shares or from owners of personal funds. *Interest is the difference between money borrowed and money returned*. It may be charged at a simple rate expressed as percentage per annum or may be compounded, in which case the interest is reinvested and adds to the principal, thereby earning more interest in subsequent years. Even if the owner invests his own capital the charge of interest is necessary to cover the income that he would have derived from it through an alternative investment or fixed deposit with a bank. *Amortization* in the periodic repayment of the principal as a uniform annual expense.

(*c*) Depreciation

Depreciation accounts for the deterioration of the equipment and decrease in its value due to corrosion, weathering and wear and tear with use. It also covers the decrease in value of equipment due to obsolescence. With rapid improvements in design and construction of plants, obsolescence factor is of enormous importance. Availability of better models with lesser overall cost of generation makes it imperative to replace the old equipment earlier than its useful life is spent. The actual life span of the plant has, therefore, to be taken as shorter than what would be normally expected out of it.

The following methods are used to calculate the depreciation cost :

(*i*) Straight line method
(*ii*) Percentage method
(*iii*) Sinking fund method
(*iv*) Unit method.

(*i*) **Straight line method.** It is the *simplest* and *commonly used method*. The life of the equipment or the enterprise is first assessed as also the residual or salvage value of the same after the estimated life span. This salvage value is *deducted* from the initial capital cost and the balance is *divided by the life as assessed in years*. Thus, the annual value of decrease in cost of equipment is found and is set aside as depreciation annually from the income. *Thus, the rate of depreciation is uniform throughout the life of the equipment*. By the time the equipment has lived out its useful life, an amount equivalent to its net cost is accumulated which can be utilised for replacement of the plant.

(*ii*) **Percentage method.** In this method the deterioration in value of equipment from year to year is taken into account and the amount of depreciation calculated upon actual residual value for each year. It thus, reduces for successive years.

(*iii*) **Sinking fund method.** 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*. In this method, the amount set aside per year consists of annual instalments and the interest earned on all the instalments.

Let, A = Amount set aside at the end of each year for n years,
n = Life of plant in years,
S = Salvage value at the end of plant life,
i = Annual rate of compound interest on the invested capital, and
P = Initial investment to install the plant.

Then, amount set aside at the end of first year = A

Amount at the end of second year

$$= A + \text{interest on } A = A + Ai = A(1 + i)$$

Amount at the end of third year

$$= A(1 + i) + \text{interest on } A(1 + i)$$
$$= A(1 + i) + A(1 + i)i$$
$$= A(1 + i)^2$$

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

Total amount accumulated in n years (say x)

= Sum of the amounts accumulated in n years *i.e.,*

$$x = A + A(1 + i) + A(1 + i)^2 + ... + A(1 + i)^{n-1}$$

$$= A\,[1 + (1 + i) + (1 + i)^2 + ... + (1 + i)^{n-1}] \quad ...(i)$$

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

$$x(1 + i) = A\,[(1 + i) + (1 + i)^2 + (1 + i)^3 + ... + (1 + i)^n] \quad ...(ii)$$

Subtracting equation (*i*) from (*ii*), we get

$$x.i = [(1 + i)^n - 1]\,A$$

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

where $x = (P - S)$

$$\therefore \quad P - S = \left[\frac{(1+i)^n - 1}{i}\right] A \quad ...(9.6)$$

or

$$A = \left[\frac{i}{(1+i)^n - 1}\right] (P - S) \quad ...(9.7)$$

(*iv*) **Unit method.** In this method *some factor is taken as a standard one and depreciation is measured by that standard*. In place of years an equipment will last, the number of hours that an equipment will last is calculated. This total number of hours is then divided by the capital value of the equipment. This constant is then multiplied by the number of actual working hours each year to get the value of depreciation for that year. In place of number of hours, the number of units of production is taken as the measuring standard.

(*d*) Operational cost

The elements that make up the operating expenditure of a power plant include the following costs :

(*i*) Cost of fuels.

(*ii*) Labour cost.

(*iii*) Cost of maintenance and repairs.

(*iv*) Cost of stores (other than fuel).

(*v*) Supervision.

(*vi*) Taxes.

Cost of fuels. In a thermal station fuel is the heaviest item of operating cost. The selection of the fuel and the maximum economy in its use are, therefore, very important considerations in thermal plant design. It is desirable to achieve the highest thermal efficiency for the plant so that fuel charges are reduced. *The cost of fuel includes not only its price at the site of purchase but its transportation and handling costs also*. In the hydroplants the absence of fuel factor in cost is responsible for lowering the operating cost. *Plant heat rate can be improved by the use of better quality of fuel or by employing better thermodynamic conditions in the plant design*.

The cost of fuel varies with the following :

(*i*) Unit price of the fuel.

(*ii*) Amount of energy produced.

(*iii*) Efficiency of the plant.

Labour cost. For plant operation labour cost is another item of operating cost. Maximum labour is needed in a thermal power plant using coal as a fuel. A hydraulic power plant or a diesel power plant of equal capacity require a lesser number of persons. In case of automatic power station the cost of labour is reduced to a great extent. However labour cost cannot be completely eliminated even with fully automatic station as they will still require some manpower for periodic inspection etc.

Cost of maintenance and repairs. In order to avoid plant breakdowns *maintenance* is necessary. *Maintenance* includes *periodic cleaning, greasing, adjustments and overhauling of equipment*. The material used for maintenance is also charged under this head. Sometimes an arbitrary percentage is assumed as maintenance cost. A good plan of maintenance would keep the sets in dependable condition and avoid the necessity of too many stand-by plants.

Repairs are necessitated when the plant breaks down or stops due to faults developing in the mechanism. The repairs may be minor, major or periodic overhauls and are charged to the depreciation fund of the equipment. This item of cost is higher for thermal plants than for hydro-plants due to complex nature of principal equipment and auxiliaries in the former.

Cost of stores (other than fuel). The items of consumable stores other than fuel include such articles as lubricating oil and greases, cotton waste, small tools, chemicals, paints and such other things. The incidence of this cost is also higher in thermal stations than in hydro-electric power stations.

Supervision. In this head the salary of supervising staff is included. A good supervision is reflected in lesser breakdowns and extended plant life. The supervising staff includes the station superintendent, chief engineer, chemist, engineers, supervisors, stores incharges, purchase officer and other establishment. Again, thermal stations, particularly coal fed, have a greater incidence of this cost than the hydro-electric power stations.

Taxes. The taxes under operating head includes the following :

(*i*) Income tax

(*ii*) Sales tax

(*iii*) Social security and employee's security etc.

9.7. SELECTION OF TYPE OF GENERATION

While choosing the type of generation the following points should be taken into consideration :

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

2. Fuel transportation cost.
3. Land required.
4. Foundation cost.
5. The availability of cooling water.
6. The type of load to be taken by the power plant.
7. Reliability in operation.
8. Plant life.
9. Cost of transmitting the energy.

9.8. SELECTION OF POWER PLANT EQUIPMENT

Selection of some important power plant equipment is discussed below :

9.8.1. Selection of Boilers

It is now well known fact that only water tube boilers (fire tube boilers not suitable) should be used for all central power stations. While selecting a boiler the following points should be taken care of :

1. Type of fuel to be burnt.
2. Type of load.
3. Cost of fuel.
4. Desirability of heat-reclaiming equipment.
5. Availability of space for boiler installation.

— The design and efficiency of the boiler is considerably influenced by the *type of fuel* used in a boiler. *A high efficiency can be obtained with coal firing as compared to oil or gas firing*. This is due to increased hydrogen loss in gaseous fuels.

— *The location of the plant* will also decide the type of fuel to be used. If the plant is nearer the coal fields, coal will be cheaper. Power plants near to the oil fields and gas wells will naturally use these fuels.

— *Coal firing* will also *influence furnace design and hence the cost of boiler*. In case of low ranking fuel such as lignites etc., pulverised firing is used. Very low fusing temperatures of coal require water cooled walls and in some cases the slag tap furnaces. The yearly minimum operating cost has to be considered which may include production cost and fixed charges. In case of anthracite coal or metallurgical coke etc. the wear on pulverising machinery is relatively much higher than that of bituminous coal.

The cost of boilers vary with the following :

(*i*) Type of boiler used.
(*ii*) Operating pressure.
(*iii*) Operating temperature.
(*iv*) Type of firing.
(*v*) Efficiency desired.

— '*Heat-reclaiming equipment*' such as *economisers* and *air preheaters* should be provided with boilers. With the addition of economisers and air preheaters the efficiency of the boiler increases from 75% to 90% and above.

— The '*increased pressure*' *affects the cost of boiler drum, boiler tubes, headers, economisers and other accessories*. Similarly high temperatures increase the cost of superheaters as higher pressure and higher temperatures require special alloy steels. *High pressures require forced circulation also. This also increases the cost but this forced circulation also increases the efficiency of the boiler*.

— The *method of firing* has also an influence on the percentage of total time for which the boiler will be available and should be considered when planning boiler capacity. Stoker firing is in general *slightly less costly than pulverised fuel firing. The pulverised fuel firing increases the efficiency*.

— *Economisers* improve the boiler efficiency by 4 to 10%. The *air preheater* further improves the boiler efficiency from 6 to 8%.

— The exhaust gases should not be cooled *below 150°C*. Below this temperature the condensation of moisture may take place and when mixed with SO_2 this moisture produces a dilute solution of H_2SO_4 which is finitely detrimental to the equipment.

— While selecting the proper economiser size as well as the size of the air preheaters *fixed* as well as *operating* charges should be considered. The fixed charges include the cost of heat recovery equipment, flue work, ducts and also increased fan cost and building cost.

9.8.2. Selection of Prime Movers

For proper selection of prime mover it is of paramount importance to construct the following curves :

(*i*) A typical daily load curve.
(*ii*) A peak-load curve.
(*iii*) A probable future-load curve.

The prime movers to be used for generating electricity could be *diesel engines, steam engines, steam turbines, gas turbines, water turbines* etc.

— While selecting a prime mover the *initial cost of a unit erected* has to be taken into consideration. The *efficiency of this unit at various loads* is also to be taken into consideration. *As the capacity of the unit increases there is a corresponding reduction in floor space per kW*.

— The selection of the prime mover depends also on the type of use whether it is used for *industrial purpose* or *for central power stations*.

Prime movers used for industrial purpose should be *non-condensing so that steam after exhausting could be used for processing*.

In case of *central power stations condensing steam turbines should be used. Diesel engines* have an advantage of higher efficiency and low cost. It also requires less labour and the initial investment is also less. But the cost of coal is less as compared to diesel oil. Also the capacity of diesel engines is limited and hence for *bigger power stations they are unsuitable*. The diesel engines are used as *standby plant* in all the central power stations whether thermal or hydro.

— In places where water is in abundance and a certain head is available hydro power plants/stations are installed. In rivers where there is a natural fall, the same could be used for driving a *water turbine* in a hydro power plant. The maintenance of hydro power plant is the cheapest.

9.8.3. Selection of Size and Number of Generating Units

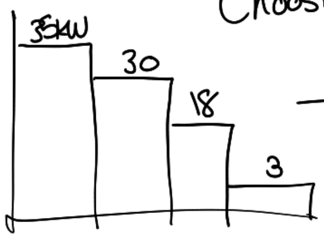
There can be no hard and fast rules, but however *looking at the load curve of the station one can guess for the total generating capacity, size and number of the units. Minimum generating capacity of a plant must be more than the predicted maximum demand*. Obviously, the minimum number of generators can be one but this will not be a wise suggestion. As the load on a power station is never constant, owing to variable demands at the different times of the day, the generator will have to run continuously at variable loads, which will be much less than the rated capacity of the generator for most of the times, *without any provision for the maintenance*. So a power station which is expected to be reliable in service, must have at *least two generators, irrespective of the total capacity of the plant*.

The following points are worth noting :

(*i*) The most appropriate way of deciding the size, and number of generating sets in a station is *to select the number of sets in such a way so as to fit in the load curve as closely as possible, so that the plant capacity may be used efficiently*.

(*ii*) Extra spare capacity is not desired as it increases the capital expenditure.

(*iii*) The main aim should be to have units of different capacities which will suitably fit in the load curve so that most of the generators when in use can be operated at nearly full load.



Choosing generating units → for here I would choose 5, 20, 40
30

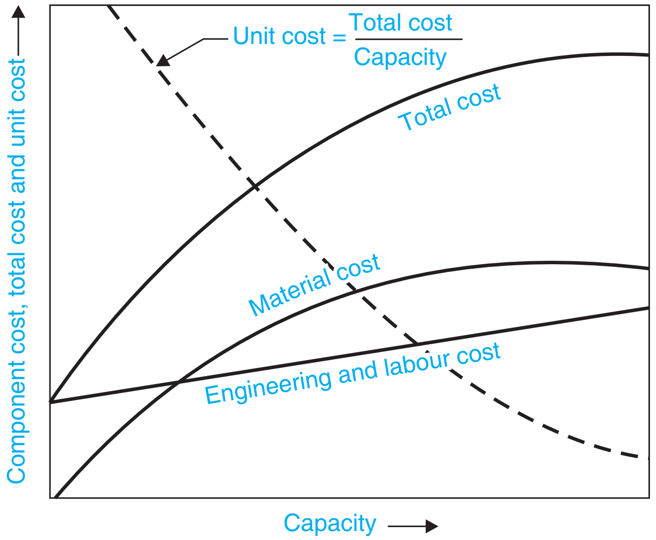


Fig. 9.4. Variation of costs of power plant *versus* its capacity.

The equipment prices are usually compared on the basis of price per unit of capacity, usually termed '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. Fig. 9.4 shows the general trend and trend of the major cost components in building a given type of machine. The following points are worth noting :

— 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 plant.

— The total cost curve follows the pattern of material cost curve. The total cost curve shows the *positive intercept at zero capacity which represents the cost of just maintaining an organisation of men and plant ready to produce*.

— The dotted curve 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 factor (0.8 to 1)*.

self study

9.9. ECONOMICS IN PLANT SELECTION

After selection of type of drive (such as steam, gas diesel or water power) which depends on availability of cheap fuels or water resources, further selection of the design and size of the equipment is primarily based upon economic consideration and a *plant that gives the lowest unit cost of*

See lecture 1/4
40 min → 50

Ex. 9.4

production is usually chosen. In case of all types of equipment the working *efficiency is generally higher with larger sizes of plants and with high load factor operation. Also, the capital cost per unit installation reduces as the plant is increased in size*. However, *a bigger size of plant would require greater investment, and possibilities of lower than optimum load factor usually increase with larger size of the plant*.

Steam power plants. In case of steam power plants the choice of *steam conditions* such as throttle pressure and temperature, is an important factor affecting operating costs and is, therefore, very carefully made. *As throttle pressure and temperature are raised the capital cost increases but the cycle efficiency is increased*. The advantage of higher pressures and temperatures is generally not apparent below capacity of 10,000 kW unless fuel cost is very high.

Heat rates may be improved further through *reheating* and *regeneration*, but again the capital cost of additional equipment has to be *balanced against gain in operating cost*.

The use of heat reclaiming devices, such as air preheaters and economisers, has to be considered from the point of economy in the consumption of fuel.

Internal combustion engine plants. In this case also the selection of I.C. engines also depends on thermodynamic considerations. *The efficiency of the engine improves with compression ratio but high pressures necessitate heavier construction of equipment which increases cost*.

The choice may also have to be made between *four-stroke* and *two-stroke* engines, the *former having higher thermal efficiency* and the *latter lower weight* and *cost*.

The cost of the *supercharger* may be justified if there *is a substantial gain in engine power which may balance the additional supercharge cost*.

Gas turbine power plant. The cost of the gas turbine power plant increases as the simple plant is modified by inclusion of other equipment such as *intercooler*, *regenerator, reheater*, etc. but the gain in thermal efficiency and thereby a reduction in operating cost may justify this additional expense in first cost.

Hydro-electric power plant. As compared with thermal stations an hydro-electric power plant has little operating cost and if sufficient water is available to cater to peak loads and special conditions for application of these plants justify, *power can be produced at a small cost*.

The *capital cost* per unit installed is *higher if the quantity of water is small*. Also, the unit cost of conveying water to the power house is greater if the quantity of water is small. The cost of storage per unit is also lower if the quantity of water stored is large.

An existing plant capacity may be *increased by storing additional water* through increasing the height of dam or by diverting water from other streams into the head reservoir. However, again it would be an economic study whether this additional cost of civil works would guarantee sufficient returns.

Some hydro-power plants may be made *automatic* or *remote controlled* to reduce the operating cost further, but the cost of automation has to be *balanced against the saving effected in the unit cost of generation*.

Interconnected hydro-steam system. In such a system where *peak loads are taken up by steam units*, the capacity of water turbine may be kept somewhat higher than the water flow capacity at peak loads, and lesser than or equal to maximum flow of river. This would make it possible for the water turbine to generate adequate energy at low cost during sufficient water flow.

Some of the principal characteristics of hydro-electric, steam and diesel power plants are listed below :

S.No.	Characteristics	Hydro-plant	Steam plant	Diesel plant
1.	*Planning and construction*	Difficult and takes long time	Easier than hydro-plant	Easiest
2.	*Civil works cost*	Highest	Lower than hydro-plant	Lowest
3.	*Running and maintenance cost* (as a fraction of total generation cost)	$\frac{1}{10}$	$\frac{1}{7}$	$\frac{1}{6}$
4.	*Overall generation cost*	Lowest	Lower than for diesel plants	Highest
5.	*Reliability*	Good	Good	Excellent

Advantages of interconnection :

Major advantages of interconnecting various power stations are :

1. Increased reliability of supply.
2. Reduction in total installed capacity.
3. Economic operation.
4. Operating savings.
5. Low capital and maintenance costs.
6. Peak loads of combined system can be carried at a *much lower cost* than what is possible with small individual system.

9.10. FACTORS AFFECTING ECONOMICS OF GENERATION AND DISTRIBUTION OF POWER

The economics of power plant operation is greatly influenced by :

(*i*) Load factor (*ii*) Demand factor

(*iii*) Utilisation factor.

Load factor. In a *hydro-electric power station* with water available and a fixed staff for maximum output, the cost per unit generated at 100% *load factor* would be *half* the cost per unit at 50% load factor. In a *steam power station* the difference would not be so pronounced since fuel cost constitutes the major item in operating costs and does not vary in the same proportion as load factor. The cost at 100% load factor in case of this station may, therefore, be about 2/3rd of the cost 50% load factor. For a *diesel station* the cost per unit generated at 100% load factor may be about 3/4th of the same cost at 50% load factor. From the above discussion it follows that :

(*i*) *Hydro-electric power station should be run at its maximum load continuously on all units.*

(*ii*) *Steam power station* should be run in such a way that *all its running units are economically loaded.*

(*iii*) *Diesel power station* should be worked for *fluctuating loads* or *as a stand by.*

Demand factor and utilisation factor. *A highly efficient station, if worked at low utilisation factor, may produce power at high unit cost.*

The time of maximum demand occurring in a system is also important. In an interconnected system, *a study of the curves of all stations is necessary to plan most economical operations.*

The endeavour should be to load the most efficient and cheapest power producing stations to the greatest extent possible. Such stations, called "*base load stations*" carry full load over 24 hours *i.e.,* for three shifts of 8 hours.

— The stations in the *medium range of efficiency* are operated only during the two shifts of 8 hours during 16 hours of average load.

— The older or *less efficient stations* are used *as peak or standby stations* only, and are operated *rarely* or for *short periods of time*.

Presently there is a tendency to use units of large capacities to reduce space costs and to handle larger loads. However, the *maximum economical benefit of large sets occurs only when these are run continuously at near full load. Running of large sets for long periods at lower than maximum continuous rating increases cost of unit generated*.

9.11. HOW TO REDUCE POWER GENERATION COST ?

The cost of power generation can be *reduced by* :

1. Using a plant of simple design that *does not need highly skilled personnel*.
2. Selecting equipment of *longer life and proper capacities*.
3. Carrying out *proper maintenance* of power plant equipment to avoid plant breakdowns.
4. Running the power stations at *high load factors*.
5. Increasing the efficiency of the power plant.
6. Keeping proper supervision, which ensures *less breakdowns* and extended plant life.

9.12. POWER PLANT—USEFUL LIFE

The useful life of a power plant is that *after which repairs become so frequent and extensive that it is found economical to replace the power plant by a new one*. Useful life of some of the power plants is given below :

Plant	*Useful life*
1. Conventional thermal power plant	20–25 years
2. Nuclear power plant	15–20 years
3. Diesel power plant	About 15 years.

The useful life of some of the equipment of a *steam power plant* is given below :

Equipment	*Useful life (years)*
1. Boilers	
(*i*) Fire tube	10–20
(*ii*) Water tube	20
2. Steam turbine	5–20
3. Steam turbo-generators	10–20
4. Condensers	20
5. Pumps	15–20
6. Coal and ash machinery	10–20
7. Feed water heaters	20–30
8. Stacks	10–30
9. Stokers	10–20
10. Transformers	15–20

11.	Motors	20
12.	Electric meters and instruments	10–15
13.	Transmission lines	10–20

9.13. ECONOMICS OF HYDRO-ELECTRIC POWER PLANTS

The cost analysis of an hydro-electric power plant is different from those of the other plants in the respect that the fixed *coal is the major item of the total cost and the operating cost is relatively much smaller* whereas in the steam and other plants, the *operating cost is a large part of the total cost*.

In a hydro-plant the total annual cost can be divided into two following categories :

1. Fixed costs :

(*i*) Interest on capital

(*ii*) Amortization of the capital

2. Running costs :

(*i*) Maintenance and repairs.

(*ii*) Operating costs including salaries and wages.

(*iii*) Rates and taxes.

(*iv*) Stores, oil and other supplies.

(*v*) Management expenses including insurance.

— The *fixed charges* of a hydro-plant are about 60 to 70% of the total cost of power and *these do not depend upon the station output*.

— The *running charges depend upon the station output, but not so much as in the thermal power plants*.

The following items go to form the *total capital outlay* or the *investment on a hydro-plant* :

(*i*) Preliminary surveys and investigations of the topography and geology of the proposed site of the plant.

(*ii*) Purchase of land (needed for adequate storage or pondage) and water rights.

(*iii*) Compensation to oustees.

(*iv*) Cost of preparation of detailed designs and specifications.

(*v*) Cost of testing the materials of construction.

(*vi*) Cost of carrying out experimental work and model tests or designs for hydraulic structures.

(*vii*) The actual cost of construction.

(*viii*) Cost relating the purchase and installation of the equipment.

(*ix*) Interest on capital during construction.

(*x*) Working capital during the period of load development.

(*xi*) Cost in respect of new roads, railway lines, residential houses and even new towns which may have to be constructed.

A typical cost analysis of a hydro-plant is as follows :

S.No.	Components	Cost
1.	Reservoir, dam and water ways	55%
2.	Land	15%
3.	Structures	10%
4.	Power plant and equipment	20%

Besides this there is an another important item called *transmission liability* which refers to the *transmission charges for conveying the electricity from the plant site to the load centre*.

— The total cost of construction of hydro-plant is *invariably higher than that of a thermal plant of equal capacity*. Therefore, the annual charges for interest and depreciation are comparatively higher.

— In case of a *hydro-plant*, the *smaller the quantity of water stored higher is the cost per kW*.

9.14. ECONOMICS OF COMBINED HYDRO AND STEAM POWER PLANTS

It has been established that if a region/country is neither rich in fuel reserves nor in hydro resources then a combined operation of hydro and steam power plants give the best results in regard to generation of electricity at *the economical cost*. The following advantages accrue from combined plants :

1. Flexibility of operation.
2. Security of supply.
3. Improved utilisation of hydro-power.
4. Spare plant.

Practically all large power systems in the world have hydro-steam interconnected. *Hydro-plant may function as a capacity plant i.e., to supply system peak with minimum flow conditions*, or it may work as an *energy plant* to replace the costly steam generated electricity by *low cost hydro power*.

In such a system (interconnected) *there should be a daily or seasonal load allocation plan set prehand so that the use of the two power systems is made to the best advantage. A certain amount of forecasting of load and capacity of the system as well as flexibility are necessary for optimum results and experience is a big factor in good co-ordinated action*.

A knowledge of system plant loading schedules for minimum production cost is as important as that of reservoir levels, pond storage and stages of low flow and heavy loads.

9.15. PERFORMANCE AND OPERATING CHARACTERISTICS OF POWER PLANTS

The *performance* of generating power plants is compared by their *average efficiency* 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 viz.* (*i*) cooling water temperature, (*ii*) quality of fuel, and (*iii*) shape of load curve. Thus, unless all plant performances are corrected to the same controlled conditions it is not a satisfactory standard of comparison.

The performance of a plant can be precisely represented by the *input-output curve* from the tests conducted on individual power plant. The input-output curve is *graphical representation* between the net energy output (L) and input (I). The input is generally expressed in millions of kcal/h or kJ/h and load output is expressed as megawatts (MW). The input to hydro-plant is measured in cusecs or m^3/s of water.

In general input-output may be represented as follows :

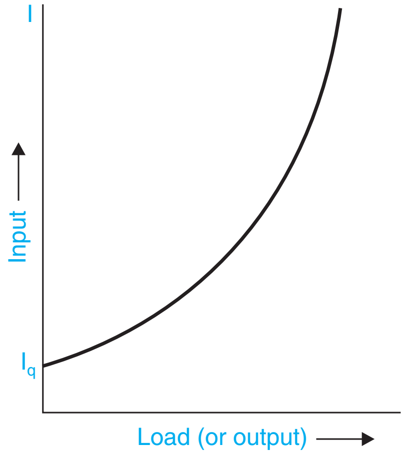
$$I = a + bL + cL^2 + dL^3$$

where I = Input,

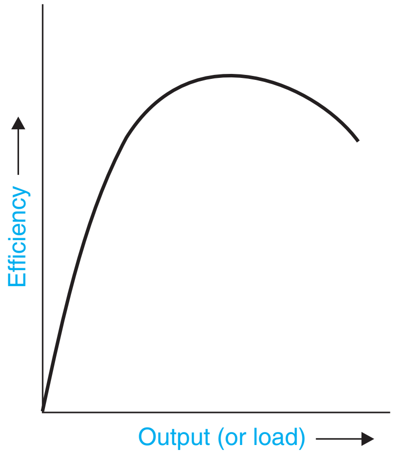
L = Output, and

a, b, c and d = Constants

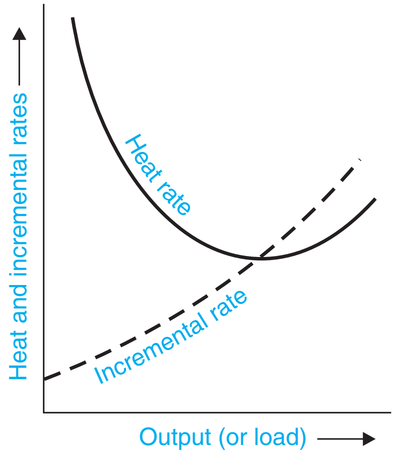
Input-output curve. Fig. 9.5 (a) shows an *input-output curve*. In order to keep the apparatus functioning at zero load, a certain input (I_0) is required *to meet frictional and heat losses*.



(a) Input - output curve.



(b) Efficiency curve.



(c) Heat rate and incremental rate curves.

Fig. 9.5

Efficiency curve. The efficiency of the power plant is defined *as the ratio of output to input*.

$$\therefore \quad \text{Efficiency,} \quad \eta = \frac{L}{I} = \frac{L}{a + bL + cL^2 + dL^3}$$

By using the above formula the efficiency *for any given load* can be calculated.

An *efficiency curve* is shown in Fig. 9.5 (b).

Heat rate and incremental rate curves. These curves can be derived from basic input-output curve.

Heat rate (HR) is defined as the *ratio of input to output*.

$$\textit{i.e.,} \quad \textit{Heat rate (HR)} = \frac{I}{L} = \frac{a + bL + cL^2 + dL^3}{L}$$

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

Heat rate curve is obtained by plotting values of heat rate against corresponding values of output. Fig. 9.5 (*c*) shows a heat rate curve.

Incremental rate (IR) is defined as the *ratio of additional input (dI) required to increase additional output (dL).*

i.e., Incremental rate (IR) = $\dfrac{dI}{dL}$.

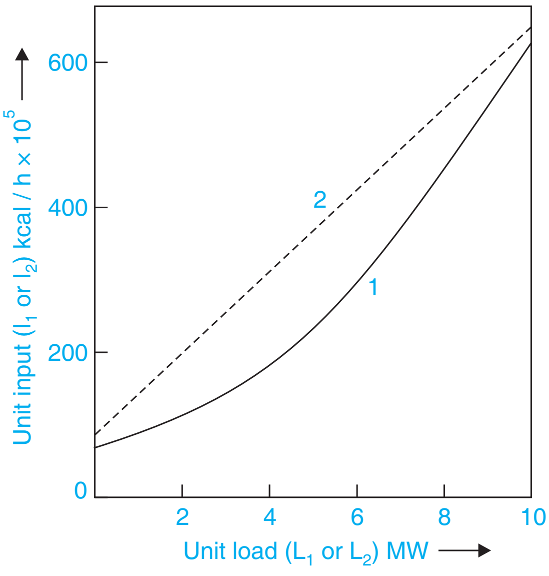
Incremental rate curve is obtained by plotting values of *IR* against corresponding values of output. Such a curve is shown in Fig. 9.5 (*c*). *This curve expresses additional energy required to produce an added unit of output at the given load.*

9.16. ECONOMIC LOAD SHARING

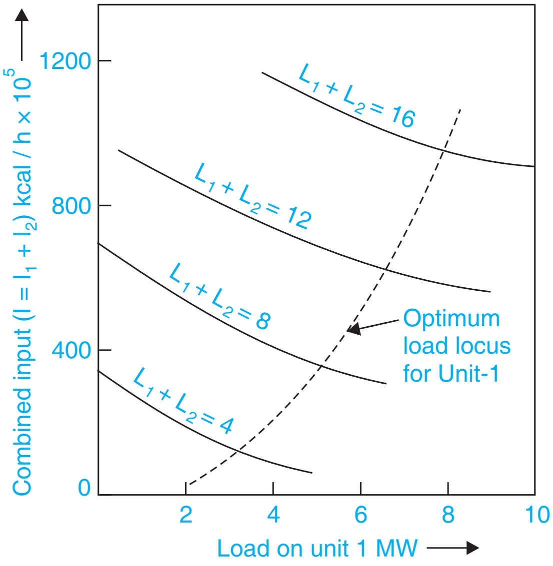
The primary objective of the design of all generating stations is the *economy*. For a power system to return a profit on the capital invested, proper operation of the plant is essential. As far as the efficiency of boilers, turbines, alternators etc. is concerned, engineers have been successful in increasing the efficiency continuously so that each unit added results in comparatively more efficient operation. Methods have also been devised for economic operation of plants at part loads and under variable load conditions. Attempts have been made to minimise the transmission losses too. Now the *only aspect that remains is the economic distribution of the output of a plant between the generators, or units within the plant.*

Let us consider two generators 1 and 2 which supply in parallel a common load. Generator 1 is more efficient than generator 2 as for the same input, output of generator 1 is more than that of generator 2.

Fig. 9.6 shows the input-output curves of the two generators/units.



(a)



(b)

Fig. 9.6

In the Fig. 9.6 (*b*) is shown the plot of combined input of generators 1 and 2 *versus* load on generator 1, for a *constant total load*.

Although generator 1 requires less input for a given output it is not essential that unit 1 should be loaded first and then generator 2. For economical loading the combined input of units 1 and 2 should be plotted against load on unit 1 for a constant total load. Let a total load of 4 MW be supplied by generators 1 and 2.

$$L = L_1 + L_2$$

where, L = combined output

L_1 = output of generator 1

L_2 = output of generator 2

Let the generator 2 supply total load of 4 MW and generator 1 supply zero load. Now corresponding to zero load on generator 1 and 4 MW on generator 2 the values of input to generator 1 (I_1) and input to generator 2 (I_2) can be determined respectively from Fig. 9.6 (*a*) and thus value of ($I_1 + I_2$) can be plotted against zero load on generator 1. Again let 2 MW be supplied by generator 1 and 2 MW be supplied by generator 2 (so that total load remains 4 MW) then values of I_1 and I_2 can be determined corresponding to 2 MW load on each generator and value of ($I_1 + I_2$) can be plotted against 2 MW load on generator 1 as shown in Fig. 9.6 (*b*). In this way curve for a total load of 4 MW can be plotted corresponding to different output of generator 1.

Similarly curve for total load of 8 MW etc. can be plotted. In these curves *there is at least one point where combined input is minimum for a given total load. Corresponding to this point of minimum, the load generator 1 can be found*. Then the load on generator 2 will be difference of total load and load on generator 1. *This load saving will be the most economical.*

This method is difficult to apply in practice as such because generally stations have got more than two generators/units and in that case the application of above principles becomes a cumbersome process.

Considering any combined constant input in Fig. 9.6 (*b*), at the point of minimum input

$$\frac{dI}{dI_1} = 0 \quad ...(i)$$

where, $I = I_1 + I_2$ = input of generator 1 + input of generator 2

= combined input to generators 1 and 2

$L = L_1 + L_2$ = output of generator 1 + output of generator 2

= combined output of generators 1 and 2

Then $$\frac{dI}{dI_1} = \frac{dI_1}{dL_1} + \frac{dI_2}{dL_1} = 0 \quad \left(\because \frac{dI}{dI_1} = 0 \right)$$

As I is constant.

$$\therefore \quad \frac{dI_1}{dL_1} = -\frac{dI_2}{dL_1} \quad ...(ii)$$

But $$\frac{dI_2}{dL_1} = \frac{dI_2}{dL_2} \times \frac{dL_2}{dL_1} \quad ...(iii)$$

Also, $L_2 = L - L_1$

$$\therefore \quad \frac{dL_2}{dL_1} = \frac{dL}{dL_1} - \frac{dL_1}{dL_1}$$

Since L is constant.

$$\therefore \quad \frac{dL}{dL_1} = 0$$

Hence, $$\frac{dL_2}{dL_1} = -\frac{dL_1}{dL_1} = -1 \quad ..(iv)$$

Substituting in (*iii*), we get

$$\frac{dI_2}{dL_1} = -\frac{dI_2}{dL_2} \quad ...(v)$$

$\therefore$ From (*ii*) and (*v*),

$$\frac{dI_1}{dL_1} = \frac{dI_2}{dL_2} \quad ...(vi)$$

Thus, *for minimum combined input to carry a given combined output, the slopes of the input-output curve 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

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

Condition for maximum efficiency :

Refer to Fig. 9.7. *The load at which efficiency will be maximum, the heat rate will be minimum at that load as efficiency is inverse of heat.*

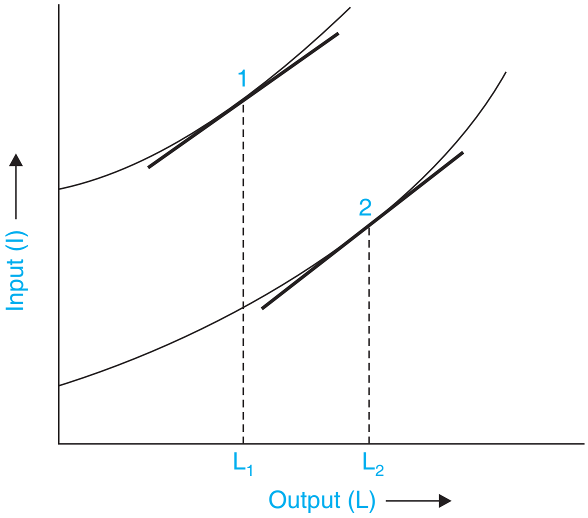


Fig. 9.7

$$\text{Efficiency} = \frac{L}{I}$$

$$\text{Heat rate } (HR) = \frac{I}{L}$$

$\therefore$ For minimum value of heat rate

$$\frac{d}{dL}(HR) = 0 \quad \text{or} \quad \frac{d}{dL}\left(\frac{I}{L}\right)$$

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

or $$\frac{I}{L} = \frac{dI}{dL}$$

This shows that efficiency will be maximum at a load where heat rate is equal to incremental heat rate.

9.17. TARIFF FOR ELECTRICAL ENERGY

9.17.1. Introduction

The cost of generation of electrical energy consists of *fixed cost and running cost*. Since the electricity generated is to be supplied to the consumers, the total cost of generation has to be recovered from the consumers. *Tariffs or energy rates are the different methods of charging the consumers for the consumption of electricity*. It is desirable to charge the consumer according to the maximum demand (kW) and the energy consumed (kWh). *The tariff chosen should recover the fixed cost, operating cost and profit etc. incurred in generating the electrical energy.*

9.17.2. Objectives and Requirements of Tariff

Objectives of tariff :

1. Recovery of cost of capital investment in generating equipment, transmission and distribution system.

2. Recovery of the cost of operation, supplies and maintenance of the equipment.
3. Recovery of the cost of material, equipment, billing and collection cost as well as for miscellaneous services.
4. A net return on the total capital investment must be ensured.

Requirements of tariff :

1. It should be easier to understand.
2. It should provide low rates for high consumption.
3. It should be uniform over large population.
4. It should encourage the consumers having high load factors.
5. It should take into account maximum demand charges and energy charges.
6. It should provide incentive for using power during off-peak hours.
7. It should provide less charges for power connection than lighting.
8. It should have a provision of penalty for low power factors.
9. It should have a provision for higher demand charges for high loads demanded at system peaks.
10. It should apportion equitably the cost of service to the different categories of consumers.

9.17.3. General Tariff Form

A large number of tariffs have been proposed from time to time and are in use. They are all derived from the following general 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 kWh during the period considered,
a = Rate per kW of maximum demand, and
b = Energy rate per kWh,
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.

Various types of tariffs :

The various types of tariffs are :

1. Flat demand rate.
2. Straight meter rate.
3. Block meter rate.
4. Hopkinson demand rate (Two-part tariff).
5. Doherty rate (Three-part tariff).
6. Wright demand rate.

1. Flat demand rate :

The flat demand rate is expressed as follows :

$$z = ax \qquad ...(9.8)$$

i.e., the bill *depends only on the maximum demand irrespective of the amount of energy consumed*. It is based on the customer's installation of energy consuming devices which is generally denoted by so many kW per month or per year. It is probably one of the early systems of charging energy rates. It was based upon the total number of lamps installed and a fixed number of hours of use per year. Hence the rate could be expressed as a price per lamp or unit of installed capacity.

Now-a-days the use of *this tariff is restricted to signal system, street lighting* etc., where the number of hours are fixed and energy consumption can be easily predicted. *Its use is very common to supplies to irrigation tubewells*, since the number of hours for which the tubewell feeders are switched on are fixed. The charge is made according to horse power of the motor installed.

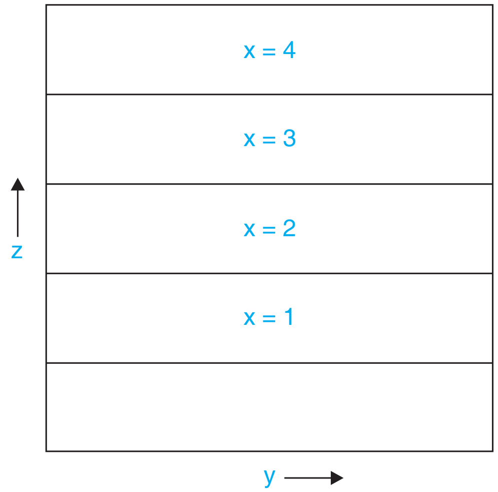


Fig. 9.8. Flat demand rate.

In this form of tariff the unit energy cost decreases progressively with an increased energy usage since the total cost remains constant. The variation in total cost and unit cost are given in Fig. 9.8.

By the use of this form of tariff the cost of metering equipment and meter reading is eliminated.

2. Straight meter rate :

The straight meter rate can be expressed in the form :

$$z = b\ .\ y \qquad ...(9.9)$$

This is the simplest form of tariff. Here the charge per unit is constant. The charges depend on the energy

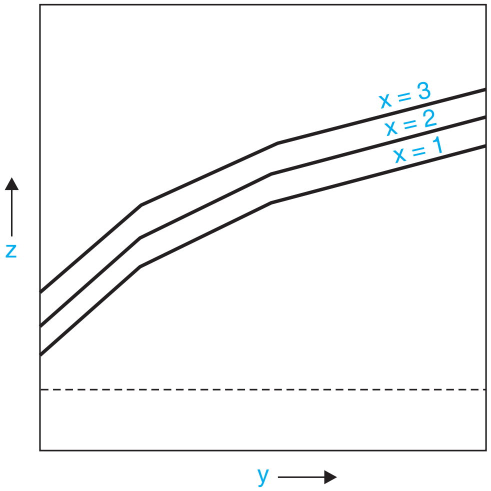


Fig. 9.12. Doherty rate (Three-part tariff).

The Doherty rate is sometimes modified by specifying the minimum demand and the minimum energy consumption that must be paid for, if they are less than the minimum values specified. In this manner the customer charge is incorporated with the demand and energy component.

6. Wright demand rate :

This tariff was introduced by Arthur Wright (of England) in 1896. This rate intensifies the inducement by lowering both the demand and energy charge for a reduction in maximum demand or in other words an improvement in load factor. *This rate is usually specified for industrial consumers who have some measure of control over their maximum demands.*

The rate is modified by stating a minimum charge which must be paid if the energy for the billing period falls below the amount by such charge. For allowing fair returns some adjustment in the rate forms are provided. Some of them are :

(*i*) Higher demand charges in summer.

(*ii*) Fuel price adjustment to provide a rate change when fuel prices deviate from the standard.

(*iii*) Wage adjustment.

(*iv*) Tax adjustment.

(*v*) Power factor adjustment.

(*vi*) Discount to be given to the customers for prompt payment of bills.

WORKED EXAMPLES

Solved

Example 9.1. *The maximum demand of a power station is 96000 kW and daily load curve is described as follows :*

Time hours	*0–6*	*6–8*	*8–12*	*12–14*	*14–18*	*18–22*	*22–24*
Load (MW)	*48*	*60*	*72*	*60*	*84*	*96*	*48*

(*i*) *Determine the load factor of power station.*

(*ii*) *What is the load factor of standby equipment rated at 30 MW that takes up all load in excess of 72 MW ? Also calculate its use factor.*

for standby equipments

Solution. Load curve is shown in Fig. 9.13.

Energy generated = area under the load curve

$= 48 \times 6 + 60 \times 2 + 72 \times 4 + 60 \times 2 + 84 \times 4 + 96 \times 4 + 48 \times 2$

$= 1632$ MWh $= 1632 \times 10^3$ kWh.

(*i*) Load factor :

$$\text{Average load} = \frac{1632 \times 10^3}{24} = 68000 \text{ kW}$$

Maximum demand = 96000 kW (given)

$$\therefore \quad \text{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}} = \frac{68000}{96000}$$

= **0.71.** **(Ans.)**

(*ii*) Load factor of standby equipment :

The standby equipment supplies

$84 - 72 = 12$ MW for 4 hours $(14 - 18)$

$96 - 72 = 24$ MW for 4 hours $(18 - 22)$

∴ Energy generated by standby equipment

$= (12 \times 4 + 24 \times 4) \times 10^3$

$= 144 \times 10^3$ kWh

Time for which standby equipment *remains in operation* (from the load curve)

$= 4 + 4 = 8$ hours

$$\text{Average} = \frac{144 \times 10^3}{8} = 18 \times 10^3 \text{ kW}$$

$$\textbf{Load factor} = \frac{18 \times 10^3}{24 \times 10^3} = \mathbf{0.75.} \quad \textbf{(Ans.)}$$

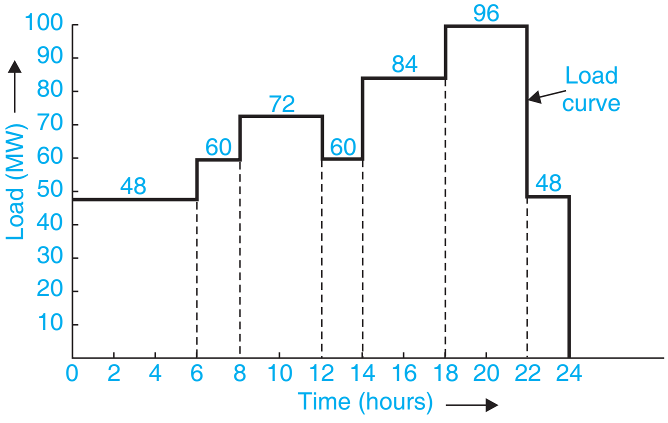


Fig. 9.13

$$\text{Use factor} = \frac{E}{C \times t'}$$

where, E = Energy generated,

C = Capacity of the standby equipment, and

t' = Actual number of hours the plant has been in operation.

$$\therefore \quad \textbf{Use factor} = \frac{144 \times 10^3}{30 \times 10^3 \times 8}$$

$$= \mathbf{0.6.} \quad \textbf{(Ans.)}$$

☞**Example 9.2.** *An electrical system experiences linear changes in load such that its daily load curve is defined as follows :*

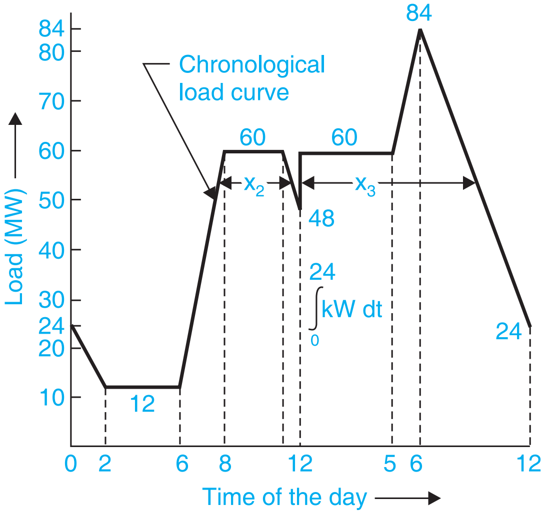
Time	*Load (MW)*
12 PM	*24*
2 AM	*12*
6 AM	*12*
8 AM	*60*
12 AM	*60*
12.30 PM	*48*
1 PM	*60*
5 PM	*60*
6 PM	*84*
12 PM	*24*

(*i*) *Plot the chronological and load duration curve for the system.*

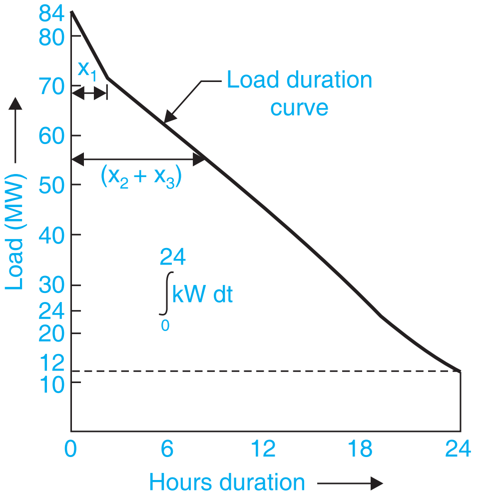
(*ii*) *Find the load factor.*

(*iii*) *What is the utilisation factor of the plant serving this load if its capacity is 120 MW.*

Solution. (*i*) **Chronological load and load duration curves :**



(a) Chronological load curve



(b) Derived load duration curve

Fig. 9.14

Chronological load and load duration curves are drawn as shown in Fig. 9.14 (*a*), (*b*). The procedure for constructing the load duration curve from chronological load curve is as follows :

— The abscissa of the load duration curve is laid off *equal to the number of hours in the chronological curve*, in this case 24 hours.

— The criterion of plotting the load duration curve *makes the abscissa at any load ordinate equal to the length of the abscissa intercepted by that load ordinate on the chronological curve*. Thus :

(*i*) At the maximum demand or peak load, the intercept is one point which will be plotted at 0 hour.

(*ii*) At 70 MW load the intercept is x_1 hours and is plotted as x_1 hour on the load duration curve.

(*iii*) At 55 MW load the intercept is a total of $(x_2 + x_3)$ and is plotted accordingly.

(*iv*) At minimum load of 12 MW the intercept covers the entire period of 24 hours.

Following points may be noted :

1. *Any point on the load duration curve is a measure of number of hours in a given period during which the given load and higher loads have prevailed.*
2. *If the chronological curve indicated a constant demand during the entire day, it would be of rectangular shape and load duration curve would be an exact duplicate.*

(*ii*) Load factor :

From the load duration curve, the average load can be estimated.

Average load for the period

$$= \frac{\text{Total energy in load curve for period}}{\text{Total number of hours in period}}$$

$$= \frac{\left(\frac{24+12}{2}\right)\times 2 + 12\times 4 + \left(\frac{12+60}{2}\right)\times 2 + 60\times 4 + \left(\frac{60+48}{2}\right)\times \frac{1}{2} + \left(\frac{48+60}{2}\right)\times \frac{1}{2} + 60\times 4 + \left(\frac{60+84}{2}\right)\times 1 + \left(\frac{84+24}{2}\right)\times 6}{24}$$

$$= \frac{36 + 48 + 72 + 240 + 27 + 27 + 240 + 72 + 324}{24}$$

$$= \frac{1086}{24} = 45.2 \text{ MW}$$

∴ **Load factor**

$$= \frac{45.2}{84} = \mathbf{0.45 \text{ or } 54\%.} \quad \textbf{(Ans.)}$$

(*iii*) Utilisation factor :

Utilisation factor

$$= \frac{\text{Maximum load}}{\text{Rated capacity of the plant}}$$

$$= \frac{84}{120} = \mathbf{0.70 \text{ or } 70\%.} \quad \textbf{(Ans.)}$$

☞**Example 9.3.** *A power station has to supply load as follows :*

Time (hours) :	*0–6*	*6–12*	*12–14*	*14–18*	*18–24*
Load (MW) :	*45*	*135*	*90*	*150*	*75*

(*i*) *Draw the load curve.*

(*ii*) *Draw load duration curve.*

(*iii*) *Choose suitable generating units to supply the load.*

(*iv*) *Calculate the load factor.*

(*v*) *Calculate the plant capacity factor.*

Solution. (*i*) Load curve :

The load curve is shown in Fig. 9.15 (*a*).

(*ii*) Load duration curve :

The load duration curve is shown in Fig. 9.15 (*b*).

(*iii*) Selection of generating units :

Load duration curve will indicate the operation schedule of different generating units.

1. One generating unit (unit 1) of 45 MW will run for **24 hours**
2. Second generating unit (unit 2) of 45 MW will run for **18 hours**
3. Third generating unit (unit 3) of 45 MW will run for **10 hours**
4. Fourth generating unit (unit 4) of 15 MW will run for **4 hours**

One additional unit (unit 5) should be kept as standby. Its capacity should be equal to the capacity of biggest set, *i.e.,* 45 MW.

Energy generated

$= 45 \times 6 + 135 \times 6 + 90 \times 2 + 150 \times 4 + 75 \times 6$

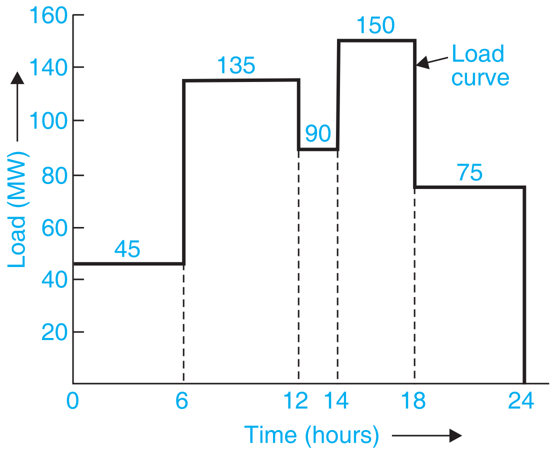
$= 270 + 810 + 180 + 600 + 450 = 2310$ MWh

Average load

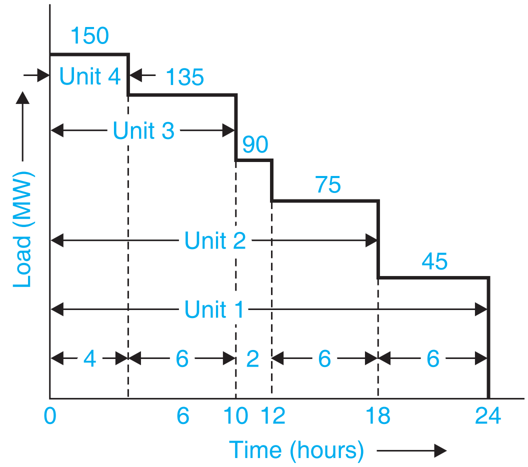
$$= \frac{2310 \times 10^3}{24} \text{ kW} = 96250 \text{ kW}$$

Maximum demand

$= 150 \times 10^3 = 150000$ kW



(a) Load curve



(b) Load duration curve

Fig. 9.15

(*iv*) **Load factor :**

$$\therefore \quad \textit{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}}$$

$$= \frac{96250}{150000} = \mathbf{0.64.} \quad \textbf{(Ans.)}$$

(*v*) **Plant capacity factor :**

Plant capacity factor

$$= \frac{E}{C \times t}$$

where, E = Energy generated (kWh),

C = Capacity of the plant (kW),

= 45 × 4 + 1 × 15 = 195 MW = 195 × 10^3 kW, and

t = Number of hours in the given period

= 24 hours.

∴ *Plant capacity factor*

$$= \frac{2310 \times 10^3}{195 \times 10^3 \times 24} = \mathbf{0.49.} \quad \textbf{(Ans.)}$$

Example 9.4. *A generating station has a maximum demand of 5000 kW, and the daily load on the station is as follows :*

Load (MW)	*1000*	*1750*	*4000*	*1500*
Time	*11 PM to 6 AM*	*6 AM to 8 AM*	*8 AM to 12.00 Noon*	*12 PM to 1 PM*
Load (MW)	*3750*	*4250*	*5000*	*2250*
Time (hours)	*1 PM to 5 PM*	*5 PM to 7 PM*	*7 PM to 9 PM*	*9 PM to 11 PM*

(*i*) *Draw the load curve.*

(*ii*) *Draw the load duration curve.*

(*iii*) *Select the size and number of generator units.*

(*iv*) *What reserve plant would be necessary ?*

(*v*) *Load factor.*

(*vi*) *Plant capacity factor.*

Solution. (*i*) **Load curve** is shown in Fig. 9.16 (*a*).

(*ii*) **Load duration curve** is shown in Fig. 9.16 (*b*).

(*iii*) **Size and number of generator units :**

From the load duration curve it is evident that generating sets of capacity 1000 kW, 1500 kW and 2500 kW will fulfil the requirement.

(*iv*) **Reserve capacity :**

Also, reserve capacity = largest size of the unit in the station = **2500 kW.** **(Ans.)**

(*v*) **Load factor :**

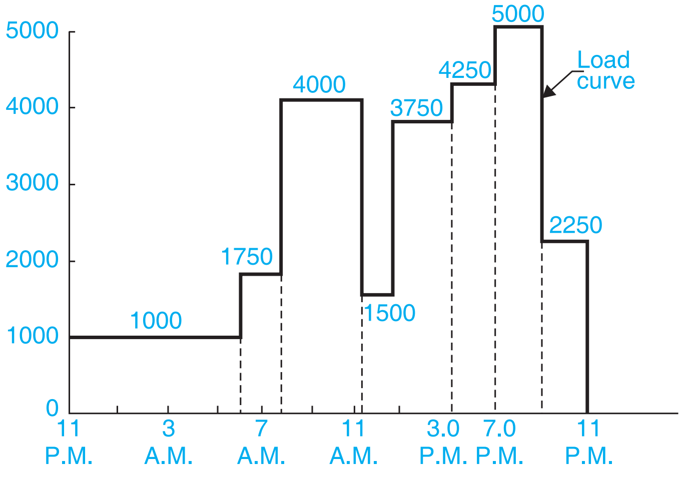
Area under the load curve gives the energy generated during 24 hours

= 1000 × 7 + 1750 × 2 + 4000 × 4 + 1500 × 1
+ 3750 × 4 + 4250 × 2 + 5000 × 2 + 2250 × 2
= 7000 + 3500 + 16000 + 1500 + 15000 + 8500
+ 10000 + 4500
= 66000 kWh

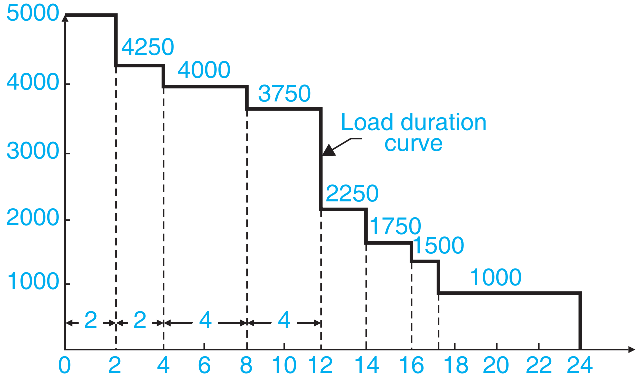
$$\text{or} \quad \text{Average load} = \frac{66000}{24} = 2750 \text{ kW}$$

$$\therefore \quad \textit{Load factor} = \frac{\text{Average load}}{\text{Maximum demand}} = \frac{2750}{5000}$$

= **0.5.** **(Ans.)**



(a) Load curve



(b) Load duration curve

Fig. 9.16

(*vi*) **Plant capacity factor :**

Plant capacity factor

$$= \frac{E}{C \times t} = \frac{66000}{(2500 + 1500 + 1000 + 2500) \times 24}$$

= **0.367.** **(Ans.)**

Example 9.5. *A 60 MW power station has an annual peak load of 50 MW. The power station supplies loads having maximum demands of 20 MW, 17 MW, 10 MW and 9 MW. The annual load factor is 0.45. Find :*

(*i*) *Average load.*

(*ii*) *Energy supplied per year.*

(*iii*) *Diversity factor.*

(*iv*) *Demand factor.*

Solution. Capacity of power station = 60 MW

Maximum demand on power station = 50 MW

(*i*) **Average load :**

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

i.e.,

$$0.45 = \frac{\text{Average load}}{50}$$

∴ *Average load* = 50 × 0.45 = **22.5 MW.** **(Ans.)**

(*ii*) **Energy supplied per year :**

Energy supplied per year

= Average load × number of hours in one year

$= (22.5 \times 10^3) \times 365 \times 24$

$= \mathbf{197.1 \times 10^6}$ **kWh.** **(Ans.)**

(*iii*) **Diversity factor :**

Diversity factor

$$= \frac{\text{Sum of individuals maximum demands}}{\text{Simultaneous maximum demand}}$$

$$= \frac{20 + 17 + 10 + 9}{50} = \frac{56}{50} = 1.12$$

Hence diversity factor = **1.12.** **(Ans.)**

(*iv*) **Demand factor :**

$$\text{Demand factor} = \frac{\text{Maximum demand}}{\text{Connected load}}$$

$$= \frac{50}{20 + 17 + 10 + 9} = \frac{50}{56} = 0.89$$

Hence, demand factor = **0.89.** **(Ans.)**

Example 9.6. *The yearly duration curve of a certain plant can be considered as a straight line from 300 MW to 80 MW. Power is supplied with one generating unit of 200 MW capacity and two units of 100 MW capacity each. Determine :*

(*i*) *Installed capacity* (*ii*) *Load factor*

(*iii*) *Plant factor* (*iv*) *Maximum demand*

(*v*) *Utilization factor.*

Solution. The load duration curve is shown in Fig. 9.17.

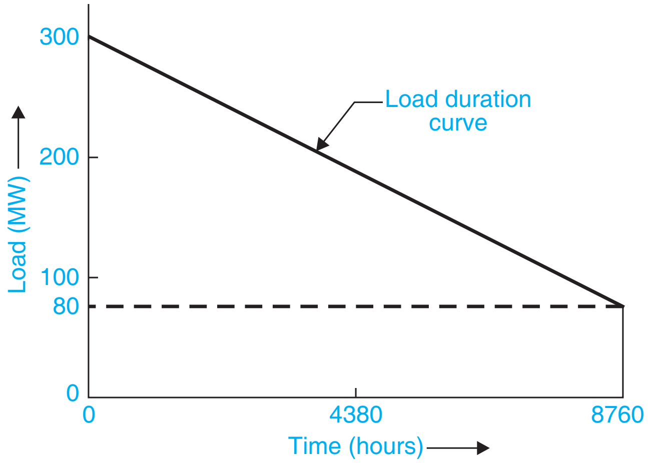


Fig. 9.17. Load duration curve.

(*i*) **Installed capacity :**

Installed capacity

= 200 + 2 × 100 = **400 MW.** **(Ans.)**

(*ii*) **Load factor :**

Load factor

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

Average load

$$= \frac{\text{Total energy in load curve for the period}}{\text{Total number of hours in the period}}$$

$$= \frac{80 \times 8760 + \frac{1}{2} \times (300 - 80) \times 8760}{8760}$$

$$= \frac{8760}{8760}\left[80 + \frac{1}{2}(300 - 80)\right] = 190 \text{ MW}$$

$$\therefore \textit{ Load factor} = \frac{190}{300} = \mathbf{0.633.} \quad \textbf{(Ans.)}$$

(*iii*) Plant factor :

$$\textit{Plant factor} = \frac{\text{Average load}}{\text{Capacity of the plant}} = \frac{190}{400}$$

$= \mathbf{0.475.}$ **(Ans.)**

(*iv*) Maximum demand = 300 MW. (Ans.)

(*v*) Utilization factor :

Utilization factor

$$= \frac{\text{Maximum load}}{\text{Rated capacity of the plant}}$$

$$= \frac{300}{400} = \mathbf{0.75.}$$ **(Ans.)**

☞**Example 9.7.** *A generating station has a maximum demand of 30 MW, a load factor of 0.6, a plant capacity of 0.48, and a plant use factor of 0.82. Find :*

(i) The daily energy produced.

(ii) The reserve capacity of the plant.

(iii) The maximum energy that could be produced if the plant were running all the time.

(iv) The maximum energy that could be produced daily, if the plant when running according to operating schedule were fully loaded.

Solution. Maximum demand of the power station

= 30 MW

Load factor = 0.6

Plant capacity = 0.48

Plant use factor = 0.82

(*i*) The daily energy produced :

$$\text{Load factor} = \frac{\text{Average demand}}{\text{Maximum demand}}$$

$$0.6 = \frac{\text{Average demand}}{30}$$

∴ Average demand

= 30 × 0.6 = 18 MW or 18000 kW

Daily energy product = Average demand × number of hours

$= 18000 \times 24 = \mathbf{4.32 \times 10^5\ kWh.}$ **(Ans.)**

(*ii*) Reserve capacity of the plant :

$$\text{Plant capacity factor} = \frac{\text{Average demand}}{\text{Installed capacity}}$$

$$0.48 = \frac{18000}{\text{Installed capacity}}$$

$$\therefore \quad \text{Installed capacity} = \frac{18000}{0.48} = 37500 \text{ kW}$$

∴ *Reserve capacity of the plant*

= Installed capacity – maximum demand

= 37500 – 30000 = **7500 kW.** **(Ans.)**

(*iii*) Maximum daily energy produced when running all the time

$= \mathbf{4.32 \times 10^5\ kWh.}$ **(Ans.)**

(*iv*) Maximum energy that could be produced daily :

Maximum energy that could be produced, operating as per operating schedule

$$= \frac{\text{Actual energy produced}}{\text{Plant use factor}}$$

$$= \frac{4.32 \times 10^5}{0.82} = \mathbf{5.268 \times 10^5\ kWh.}$$ **(Ans.)**

Example 9.8. *A power station has the following loads :*

1. Residential lighting load :

Maximum demand = *1200 kW*

Load factor = *0.21*

Diversity between consumers = *1.32*

2. Commercial load :

Maximum demand = *2400 kW*

Load factor = *0.32*

Diversity between consumers = *1.2*

3. Industrial load :

Maximum demand = *6000 kW*

Load factor = *0.82*

Diversity between consumers = *1.22*

Overall diversity factor may be taken as 1.42.

Determine the following :

(i) Maximum demand on system.

(ii) Daily energy consumption (total).

(iii) Overall load factor.

(iv) Connected load (total) assuming that demand factor for each load is unity.

Solution. (*i*) Maximum demand on system :

Group diversity factor

$$= \frac{\text{Sum of individual maximum demands}}{\text{Actual maximum demand of the group}}$$

$$\therefore \quad 1.42 = \frac{1200 + 2400 + 6000}{\text{Maximum demand on system}}$$

i.e., Maximum demand on system

$$= \frac{1200 + 2400 + 6000}{1.42}$$

= **6760.5 kW.** **(Ans.)**

(*ii*) Daily energy consumption :

$$\text{Load factor} = \frac{\text{Average demand}}{\text{Maximum demand}}$$

or Average demand = Maximum demand × load factor

= 1200 × 0.21 + 2400 × 0.32 + 6000 × 0.82

= 5940 kW

∴ *Daily energy consumption*

= 5940 × 24 = **142560 kWh.** **(Ans.)**

(*iii*) Overall load factor :

$$\text{Overall load factor} = \frac{\text{Average demand}}{\text{Maximum demand}}$$

$$= \frac{5940}{6760.5} = \mathbf{0.878.} \quad \textbf{(Ans.)}$$

(*iv*) Connected load :

Maximum demand

$$= 1200 \times 1.32 + 2400 \times 1.2 + 6000 \times 1.22$$

$$= 11784 \text{ kW}$$

Connected load

$$= \frac{\text{Maximum demand}}{\text{Demand factor}} = \frac{11784}{1}$$

$$= \mathbf{11784\ kW.} \quad \textbf{(Ans.)}$$

Example 9.9. *The following data relates to a steam power plant :*

Maximum demand = 30000 kW
Load factor = 0.42
Coal consumption = 1.1 kg/kWh
Boiler efficiency = 84%
Turbine efficiency = 88%
Price of coal = ₹ 70 per tonne.

Determine the following :

(i) Thermal efficiency of the plant.

(ii) Coal bill of the plant for one year.

Solution. (*i*) Thermal efficiency of the plant :

Thermal efficiency of the plant

= Boiler efficiency × turbine efficiency

$= 0.84 \times 0.88 =$ **0.7392 or 73.92%.** **(Ans.)**

(*ii*) Coal bill :

Average demand on station = Maximum demand × load factor

$$= 30000 \times 0.42 = 12600 \text{ kW}$$

∴ Energy generated per year

$$= 12600 \times (365 \times 24) \text{ kWh}$$

∴ Coal consumption

$$= 12600 \times (365 \times 24) \times 1.1 \text{ kg per year}$$

∴ *Coal bill*

$$= \frac{12600 \times (365 \times 24) \times 1.1 \times 70}{1000}$$

= **₹ 8498952.** **(Ans.)**

☞**Example 9.10.** *A power station is to supply for regions of load whose peak loads are 10 MW, 5 MW, 8 MW and 7 MW. The diversity factor of the load at the station is 1.5 and the average annual load factor is 0.6. Calculate :*

(i) Maximum demand on the station.

(ii) Annual energy supplied from the station.

Suggest the installed capacity and the number of units taking all aspects into account.

Solution. (*i*) Maximum demand :

Maximum demand on power station

$$= \frac{\text{Sum of individual maximum demands}}{\text{Diversity factor}}$$

$$= \frac{10 + 5 + 8 + 7}{1.5}$$

= **20 MW or 20000 kW.** **(Ans.)**

(*ii*) Annual energy supplied :

Average load = Maximum demand × load factor

$$= 20000 \times 0.6 = 12000 \text{ kW}$$

Annual energy supplied from the station

$$= \text{Average load} \times (365 \times 24)$$

$$= 12000 \times (365 \times 24)$$

$$= \mathbf{105.12 \times 10^6\ kWh.} \quad \textbf{(Ans.)}$$

Installed capacity and number of units :

Considering 50% increase in maximum demand on the power station in next five years, the *installed capacity* should be **30000 kW or 30 MW.** **(Ans.)**

Select, four similar units each of 7.5 MW capacity because minimum number of spare parts will be required to be stored, at the same time *three units can supply present maximum demand and fourth unit can be taken out for routine maintenance or during breakdown without any disruption in supply*.

Example 9.11. *The peak load on a 50 MW power station is 39 MW. It supplies power through four transformers whose connected loads are 17, 12, 9 and 10 MW. The maximum demands on these transformers are 15, 10, 8 and 9 MW respectively. If the annual load factor is 50% and the plant is operating for 65% of the period in a year, find out the following :*

(i) Average load on the station

(ii) Energy supplied per year

(iii) Demand factor

(iv) Diversity factor

(v) Power station use factor.

Solution. Power station rated capacity

= 50 MW or 50000 kW

Maximum demand on the power station

= 39 MW or 39000 kW

Sum of connected load

$= 17 + 12 + 9 + 10 = 48$ MW or 48000 kW

Sum of maximum demands on the transformers

$= 15 + 10 + 8 + 9 = 42$ MW or 42000 kW

Annual load factor = 50% or 0.5

Plant operating period

$= 0.65 \times (365 \times 24) = 5964$ hours.

(*i*) Average load on the station :

Average load on the station = Maximum demand × load factor

$= 39000 \times 0.5 = \mathbf{19500\ kW.}$ **(Ans.)**

(*ii*) **Energy supplied per year :**

Energy supplied per year

$= \text{Average load} \times (365 \times 24)$

$= 19500 \times 8760$

$= \mathbf{170.82 \times 10^6\ kWh.}$ **(Ans.)**

(*iii*) **Demand factor :**

$$\textit{Demand factor} = \frac{\text{Maximum demand}}{\text{Sum of connected load}}$$

$$= \frac{39000}{48000} = \mathbf{0.8125.} \quad \textbf{(Ans.)}$$

(*iv*) **Diversity factor :**

$$\textit{Diversity factor} = \frac{\text{Sum of maximum demands}}{\text{Maximum demand}}$$

$$= \frac{42000}{39000} = \mathbf{1.077.} \quad \textbf{(Ans.)}$$

(*v*) **Power station use factor :**

Use factor

$$= \frac{\text{Energy generated per year}}{\text{Rated capacity} \times \text{number of operating hours}}$$

$$= \frac{170.82 \times 10^6}{50000 \times 5694} = \mathbf{0.6\ or\ 60\%.} \quad \textbf{(Ans.)}$$

Example 9.12. *A base load power station and standby power station share a common load as follows :*

Base load station annual output $= 180 \times 10^6$ *kWh*

Base load station capacity $= 42$ *MW*

Maximum demand on base load station

$= 36$ *MW*

Standby station capacity $= 22$ *MW*

Standby station annual output $= 17 \times 10^6$ *kWh*

Maximum demand (peak load) on stand by station

$= 18$ *MW*

Determine the following for both power stations :

(*i*) *Load factor.*

(*ii*) *Capacity (or plant) factor.*

Solution. Base load station :

$$\text{Average load} = \frac{180 \times 10^6}{365 \times 24} = 20548\ \text{kW}$$

(*i*) **Load factor** $= \dfrac{\text{Average load}}{\text{Maximum demand}} = \dfrac{20548}{36 \times 10^3}$

$= \mathbf{0.57.}$ **(Ans.)**

(*ii*) **Capacity factor**

$$= \frac{\text{Energy generated}}{\text{Capacity of plant} \times (24 \times 365)}$$

$$= \frac{180 \times 10^6}{42 \times 1000 \times 24 \times 365}$$

$= \mathbf{0.489.}$ **(Ans.)**

Standby power station :

$$\text{Annual average load} = \frac{17 \times 10^6}{365 \times 24} = 1940.6\ \text{kW}$$

(*i*) **Load factor**

$$= \frac{\text{Average load}}{\text{Maximum demand}} = \frac{1940.6}{18 \times 1000}$$

$= \mathbf{0.1078.}$ **(Ans.)**

(*ii*) **Capacity factor** $= \dfrac{\text{Energy generated}}{\text{Capacity} \times (24 \times 365)}$

$$= \frac{17 \times 10^6}{22 \times 1000 \times 24 \times 365}$$

$= \mathbf{0.088.}$ **(Ans.)**

☞**Example 9.13.** *A base load station having a capacity of 18 MW a standby station having a capacity of 20 MW share a common load. Find (i) annual load factor, (ii) use factor, and (iii) capacity factor of the two power stations from the following data :*

Annual standby station output

$= 7.35 \times 10^6$ *kWh*

Annual base load station output

$= 101.35 \times 10^6$ *kWh*

Peak load on the standby station

$= 12$ *MW*

Hours of use of standby station during the year

$= 2190$ *hours.*

Solution. Standby station :

Capacity of standby station

$= 20$ MW or 20000 kW

Maximum demand on standby station

$= 12$ MW or 12000 kW

Annual standby station output

$= 7.35 \times 10^6$ kWh

Hours of use of standby station during the year

$= 2190$ hours

Annual average load of standby station

$$= \frac{\text{Output in kWh}}{365 \times 24} = \frac{7.35 \times 10^6}{365 \times 24}$$

$= 839$ kW

(*i*) **Annual load factor :**

Annual load factor

$$= \frac{\text{Annual average load}}{\text{Maximum demand}} = \frac{839}{12000}$$

$= \mathbf{0.07\quad or\quad 7\%.}$ **(Ans.)**

(*ii*) **Use factor :**

Use factor

$$= \frac{\text{Total kWh generated}}{\text{Rated capacity of station} \times \text{Number of operating hours}}$$

$$= \frac{7.35 \times 10^6}{20000 \times 2190}$$

= **0.1678 or 16.78%. (Ans.)**

(*iii*) Capacity factor :

$$\textit{Capacity factor} = \frac{\text{Average load}}{\text{Rated capacity}} = \frac{839}{20000}$$

= **0.0419 or 4.19%. (Ans.)**

Base load station :

Capacity of base load station

= 18 MW or 18000 kW

Assume maximum demand on base load station equal to its rated capacity *i.e.,* 18 MW.

Annual base load station output

= 101.35×10^6 kWh

Annual average load of base load station

$$= \frac{\text{Output in kWh}}{365 \times 24}$$

$$= \frac{101.35 \times 10^6}{365 \times 24} = 11570 \text{ kW}$$

(*i*) Annual load factor :

Annual load factor

$$= \frac{\text{Annual average load}}{\text{Maximum demand}}$$

$$= \frac{11570}{18000} = \mathbf{0.643} \text{ or } \mathbf{64.3\%}. \text{ (Ans.)}$$

(*ii*) Use factor :

Use factor

$$= \frac{\text{Total kWh generated}}{\text{Rated capacity} \times \text{Number of operating hours}}$$

$$= \frac{101.35 \times 10^6}{18000 \times (365 \times 24)}$$

= **0.643 or 64.3%. (Ans.)**

(*iii*) Capacity factor :

$$\textit{Capacity factor} = \frac{\text{Average load}}{\text{Rated capacity}} = \frac{11570}{18000}$$

= **0.643 or 64.3%. (Ans.)**

COST ANALYSIS

Example 9.14. *Determine the annual cost of a feed water softner from the following data :*

Cost = *₹ 96000*
Salvage value = *5%*
Life = *10 years*
Annual repair and maintenance cost = *₹ 3000*
Annual cost of chemicals = *₹ 6000*
Labour cost per month = *₹ 360*
Interest on sinking fund = *5%.*

Solution. Capital cost, P = ₹ 96000.

Salvage value, $S = \frac{5}{100} \times 96000$ = ₹ 4800

Rate of interest on sinking fund, i = 5% or 0.05

Life, n = 10 years

∴ Annual sinking fund payment

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

$$= (9600 - 4800)\left[\frac{0.05}{(1+0.05)^{10} - 1}\right]$$

= ₹ 7250.8

Total cost per year :

Annual sinking fund

= ₹ 7250.8

Annual repair and maintenance cost

= ₹ 3000

Annual cost of chemicals

= ₹ 6000

Annual labour cost

= (360 × 12) = ₹ 4320

∴ *Total cost per year*

= 7250.8 + 3000 + 6000 + 4320

= **₹ 20570.8. (Ans.)**

Example 9.15. *The output of a generating station is 500 × 10^6 kWh per year and average load factor is 0.7. If the annual fixed charges are ₹ 50 per kW of installed plant and annual running charges are 5 per kWh, what is the cost per kWh of energy at the bus bar.*

Solution. Output energy per annum = 500 × 10^6 kWh

Average load

$$= \frac{\text{Annual average load}}{365 \times 24} = \frac{500 \times 10^6}{365 \times 24}$$

= 57077 kW

Maximum demand

$$= \frac{\text{Average load}}{\text{Load factor}} = \frac{57077}{0.7}$$

= 81538 kW

Assuming installed capacity equal to maximum demand,

Fixed charges = 50 × 81538 = ₹ 4076900

Running charges

$$= ₹\ \frac{5}{100} \times 500 \times 10^6 = ₹\ 25000000$$

Total annual charges

= ₹ 25000000 + ₹ 4076900

= ₹ 29076900

Cost of energy at bus-bar

$$= \frac{\text{Total annual charges}}{\text{Output energy per annum}}$$

$$= \frac{29076900}{500 \times 10^6}$$

= **₹ 0.058 or 5.8 p/kWh. (Ans.)**

Example 9.16. *From the following data calculate the cost of generation per unit delivered from the power plant :*

Installed capacity of the power plant = 200 MW

Annual load factor = 0.4

Capital cost of power plant = ₹280 lacs

Annual cost of fuel, oil, salaries, taxation

= ₹60 lacs.

Interest and depreciation = 13%.

Solution. Installed capacity of the power plant

= 200 MW or 200 × 10^3 kW

Assuming maximum demand equal to installed capacity,

Maximum demand = 200 × 10^3 kW

Annual load factor = 0.4

Total units generated per annum

= Maximum demand × load factor × (365 × 24)

= 200 × 10^3 × 0.4 × (365 × 24) = 700.8 × 10^6 kWh

Capital cost of the power plant = ₹ 280 × 10^5

Annual interest and depreciation

$$= ₹\ 280 \times 10^6 \times \frac{13}{100} = ₹\ 3.64 \times 10^6$$

Annual cost of fuel, oil, salaries, taxation etc.

= ₹ 60 × 10^5 or 6 × 10^6

Total annual cost

= ₹ 3.64 × 10^6 + ₹ 6 × 10^6 = ₹ 9.64 × 10^6

Generating cost

$$= \frac{\text{Total annual cost}}{\text{Total units generated per annum}}$$

$$= \frac{9.64 \times 10^6}{700.8 \times 10^6}$$

= **₹ 0.0137 or 1.37 p/kWh. (Ans.)**

☞**Example 9.17.** *The following data relate to a 10 MW power station :*

Cost of plant = ₹1200 per kW

Interest, insurances and taxes

= 5% per annum

Depreciation = 5%

Cost of primary distribution

= ₹500000

Interest, insurances, taxes and depreciation

= 5%

Cost of coal including transportation

= ₹4.4 per kN

Operating cost

= ₹500000

Plant maintenance cost :

(i) Fixed = ₹20000 per annum

(ii) Variable = ₹30000 per annum

Installed plant capacity

= 10000 kW

Maximum demand

= 9000 kW

Annual load factor

= 0.6

Consumption of coal

= 255000 kN

Determine the following :

(i) Cost of power generation per kW per year.

(ii) Cost per kWh generated.

(iii) Total cost of generation per kWh.

Transmission or primary distribution chargeable to generation.

Solution. Installed capacity of plant

= 10 MW or 10000 kW

Total cost of plant

= ₹ 10000 × 1200 = ₹ 12 × 10^6

Annual interest, insurances and taxes

= ₹ 0.05 × 12 × 10^6 = ₹ 0.06 × 10^6

= ₹ 600000

Annual depreciation

= ₹ 0.05 × 12 × 10^6 = ₹ 0.6 × 10^6

= ₹ 600000

Annual interest, insurance, taxes and depreciation on primary distribution

= ₹ 0.05 × 500000 = ₹ 25000

Annual plant maintenance cost (fixed)

= ₹ 20000

Total fixed cost

= ₹ (600000 + 600000 + 25000 + 20000)

= ₹ 1245000

Annual operating cost

= ₹ 500000

Annual plant maintenance cost (variable)

= ₹ 30000

Annual cost of coal

= ₹ 4.4 × 255000 = ₹ 1122000

Total annual running cost

= ₹ (500000 + 300000 + 1122000)

= ₹ 1652000

Maximum demand

= 9000 kW

Annual load factor

= 0.6

Average load

= $9000 \times 0.6 = 5400$ kW

Annual energy generated

= $5400 \times 365 \times 24 = 47.3 \times 10^6$ kWh

(*i*) Cost of power generation per kW per year :

Annual cost per kW of maximum demand

$$= \frac{\text{Fixed cost per annum}}{\text{Maximum demand}}$$

$$= \frac{1245000}{9000} = ₹\ \mathbf{138.33.} \quad \textbf{(Ans.)}$$

(*ii*) Cost per kWh generated :

Annual cost/kWh

$$= \frac{\text{Annual running cost}}{\text{Annual energy generated}}$$

$$= \frac{1652000}{47.3 \times 10^6} = ₹\ \mathbf{0.035\ \ or\ \ 3.5\ p.} \quad \textbf{(Ans.)}$$

(*iii*) Total cost per kWh :

Total cost per kWh

$$= \frac{\text{Total annual cost}}{\text{Annual energy generated}}$$

$$= \frac{1245000 + 1652000}{47.3 \times 10^6}$$

= ₹ **0.06 or 6 p.** **(Ans.)**

Example 9.18. *Annual 200 MW steam power station is estimated to cost ₹350 millions. Other costs are as follows :*

Insurance and taxes

= *₹5 lacs per annum*

Fuel and lubricants

= *₹70 lacs per annum*

Transport and storage

= *₹10 lacs per annum*

Salaries and wages

= *₹12 lacs per annum*

Miscellaneous

= *₹2 lacs per annum*

Reckoning interest and depreciation at 15% per annum of capital cost, determine :

The cost of energy generated per unit if the power station works at an average load factor of 0.6. What would it be, if the load factor be increased to 75% with a consequent increase in fuel costs by 10%, other costs remaining the same ?

Solution. Capacity of steam power station

= 200 MW or 200000 kW

Cost of power station

= ₹ 350 millions = ₹ 350×10^6

Annual cost of insurance and taxes

= ₹ 5 lacs = ₹ 0.5×10^6

Annual cost of fuel and lubricants

= ₹ 70 lacs = ₹ 7×10^6

Annual cost of transport and storage

= ₹ 10 lacs = ₹ 1×10^6

Annual cost of salaries and wages

= ₹ 12 lacs = ₹ 1.2×10^6

Annual miscellaneous cost

= ₹ 2 lacs = ₹ 0.2×10^6

Annual interest and depreciation

$$= ₹\ 350 \times 10^6 \times \frac{15}{100} = ₹\ 52.5 \times 10^6$$

Total annual cost

= ₹ $(0.5 + 7 + 1 + 1.2 + 0.2 + 52.5) \times 10^6$

= ₹ 62.4×10^6

Total energy generated per annum

= Maximum demand × average load factor × (365 × 24)

= $200000 \times 0.6 \times (365 \times 24)$

= 1051.2×10^6 kWh

Cost of generation

$$= \frac{\text{Total annual cost}}{\text{Total units generated}}$$

$$= \frac{62.4 \times 10^6}{1051.2 \times 10^6} = ₹\ \mathbf{0.0594\ per\ kWh}$$

or 5.94 paise per kWh. **(Ans.)**

If the load factor is improved to 75% :

Total energy generated per annum

= $200000 \times 0.75 \times (365 \times 24)$

= 1314×10^6 kWh

Annual operating cost

= ₹ $(0.5 + 7 \times 1.1 \times 10^6 + 1 + 1.2 + 0.2 + 52.5) \times 10^6$

= ₹ 63.1×10^6

Cost of generation

$$= \frac{\text{Total annual cost}}{\text{Total units generated}}$$

$$= \frac{63.1 \times 10^6}{1314 \times 10^6} = ₹\ \mathbf{0.048\ per\ kWh}$$

or 4.8 paise per kWh. **(Ans.)**

Example 9.19. *A steam station has two 110 MW units. Following cost data are given :*

Particulars	***Units A***	***Units B***
Capital cost	*₹2400 per kW*	*₹3000 per kW*
Fixed charge rate	*10%*	*10%*
Capital factor	*0.55*	*0.60*
Fuel consumption	*1 kg/kWh*	*0.9 kg/kWh*
Fuel cost	*₹96 per 1000 kg*	*₹96 per 1000 kg*

Annual cost of operation, labour maintenance and supplies	*20% of annual fuel cost*	*15% of annual fuel cost*
Utilisation factor	*1*	*1*

Calculate the following :

(*i*) *Annual plant cost and generation cost of unit A.*

(*ii*) *Annual plant cost and generation cost of unit B.*

(*iii*) *Overall generation cost of the station.*

Solution. (*i*) **Annual plant cost and generation cost of unit A :**

Annual fixed cost of unit A

$= \frac{10}{100} \times 2400 \times (100 \times 1000)$

$= ₹\ 26.4 \times 10^6$

Annual energy output

= Maximum demand × capacity factor × no. of hours

$= (100 \times 1000) \times 0.55 \times (356 \times 24)$

$= 52.998 \times 10^7$ kWh

Annual fuel consumption

$= 1 \times 52.998 \times 10^7$

$= 52.998 \times 10^7$ kg

Fuel cost $= \frac{96}{1000} \times 52.998 \times 10^7 = ₹\ 50.87 \times 10^7$

Annual cost of operating labour, maintenance and supplies

= 20% of annual cost

$= \frac{20}{100} \times 50.87 \times 10^6 = ₹\ 10.174 \times 10^6$

The annual operating cost of unit A

= Annual fuel cost + annual cost of operation, labour and maintenance

$= ₹\ (50.87 \times 10^6 + 10.174 \times 10^6)$

$= ₹\ 61.044 \times 10^6$

Annual plant cost of unit A

= Annual fixed cost + annual operating cost

$= ₹\ (26.4 \times 10^6 + 61.044 \times 10^6)$

$= ₹\ \mathbf{87.444 \times 10^6}$. **(Ans.)**

Generation cost of unit A

$$= \frac{\text{Annual plant cost}}{\text{Annual energy output}}$$

$$= \frac{87.444 \times 10^6}{52.998 \times 10^7} = ₹\ \mathbf{0.165}$$

or 165.5 p/kWh. (Ans.)

(*ii*) **Annual plant cost and generation cost of unit B :**

Annual fixed cost of unit B

$= ₹\ \frac{10}{100} \times 3000 \times 110 \times 1000 = ₹\ 33 \times 10^6$

Expected annual energy output

$= (110 \times 1000) \times (365 \times 24) \times 0.6$

$= 57.816 \times 10^7$ kWh

Annual fuel consumption

$= 0.9 \times 57.816 \times 10^7 = 52.0344 \times 10^7$ kg

Fuel cost $= \frac{96}{100} \times 52.0344 \times 10^7 = ₹\ 49.95 \times 10^6$

Annual cost of maintenance, repair etc.

$= ₹\ \frac{15}{100} \times 49.95 \times 10^6 = ₹\ 7.4925 \times 10^6$

Annual operating cost

= Fuel cost + maintenance cost

$= ₹\ (49.95 \times 10^6 + 7.4925 \times 10^6)$

$= ₹\ 57.4425 \times 10^6$

Annual plant cost of unit B

= Fixed cost + operating cost

$= ₹\ 33 \times 10^6 + 57.4425 \times 10^6$

$= ₹\ \mathbf{90.4425 \times 10^6}$ **(Ans.)**

Generation cost of unit B

$$= \frac{\text{Annual plant cost}}{\text{Annual energy output}}$$

$$= \frac{90.4425 \times 10^6}{57.816 \times 10^7}$$

= **₹ 0.1564 or 15.64 p/kWh. (Ans.)**

(*iii*) **Overall generation cost of the station**

$$= \frac{\text{Sum of annual plant cost of both units}}{\text{Sum of energy supplied}}$$

$$= \frac{87.444 \times 10^6 + 90.4425 \times 10^6}{52.998 \times 10^7 + 57.816 \times 10^7}$$

= **₹ 0.16 or 16 p/kWh. (Ans.)**

☞**Example 9.20.** *The annual costs of operating a 15000 kW thermal power station are as follows :*

Cost of plant = ₹ 1080 per kW

Interest, insurance, taxes on plant = 5 per cent

Depreciation = 5 per cent

Cost of primary distribution system = ₹ 600000

Interest, insurance, taxes and depreciation on primary distribution system = 5 per cent

Cost of secondary distribution system = ₹ 1080000

Interest, taxes, insurance and depreciation on secondary distribution system = 5 per cent

Maintenance of secondary distribution system = ₹ 216000

Plant maintenance cost

(i) Fixed cost = ₹ 36000

(ii) Variable cost = ₹ 48000

Operating costs = ₹ 720000

Cost of coal = ₹ 7.2 per kN

Consumption of coal = 300000 kN

Dividend to stock holders = ₹ 1200000

Energy loss in transmission = 10 per cent

Maximum demand = 14000 kW

Diversity factor = 1.5

Load factor = 0.7

Determine : (i) Charge per kW per year

(ii) Rate per kWh.

Solution. Maximum demand = 14000 kW

$$\text{Load factor} = 0.7 = \frac{\text{Average load}}{\text{Maximum demand}}$$

∴ Average load = 0.7 × 14000 = 9800 kW

∴ Energy generated per year

$$= 9800 \times (365 \times 24)$$
$$= 85.8 \times 10^6 \text{ kWh}$$

Cost of plant = Capacity of plant × cost per kW

$$= 15000 \times 1080 = ₹\ 16.2 \times 10^6$$

Interest, insurances, taxes on plant

$$= \frac{5}{100} \times 16.2 \times 10^6 = ₹\ 810000$$

$$\text{Plant depreciation} = \frac{5}{100} \times 16.2 \times 10^6 = ₹\ 810000$$

Cost of primary distribution system = ₹ 600000

Interest, insurance, taxes, depreciation on primary distribution system

$$= \frac{5}{100} \times 600000 = ₹\ 30000$$

Cost of secondary distribution system = ₹ 1080000

$$= \frac{5}{100} \times 1080000 = ₹\ 54000$$

Cost of coal = 7.2 × 300000 = ₹ 2160000.

(*i*) Charge per kW per year :

Fixed costs

Interest, taxes and insurance on plant

= ₹ 810000

Plant depreciation

= ₹ 810000

Interest, taxes, insurance and depreciation on :

Primary distribution system

= ₹ 30000

Secondary distribution system

= ₹ 54000

Fixed part of plant maintenance

= ₹ 36000

Dividend of stock-holder

= ₹ 1200000

∴ Total fixed cost

= ₹ 2940000

Sum of maximum demand of consumers

= Maximum demand × diversity factor

= 14000 × 1.5 = 21000 kW

$$\textbf{Charge per kW per year} = \frac{2940000}{21000}$$

= **₹ 140 per kW.** **(Ans.)**

(*ii*) Rate per kWh :

Variable costs

Cost of coal = ₹ 2160000

Plant maintenance = ₹ 48000

Operating costs = ₹ 720000

Maintenance of secondary distribution system

= ₹ 216000

Total variable cost = ₹ 3144000

Energy loss in transmission

= 10 per cent

∴ Net energy transmitted

$$= 0.9 \times 85.8 \times 10^6$$
$$= 77.22 \times 10^6 \text{ kWh}$$

$$\therefore \quad \textbf{Rate per kWh} = \frac{3144000}{77.22 \times 10^6}$$

= **₹ 0.0407**

or 4.07 p/kWh. **(Ans.)**

Example 9.21. *It is proposed to supply a load with a maximum demand of 100 MW and a load factor of 0.4. Choice is to be made from nuclear, hydro and steam power plants. Calculate the overall cost per kWh in each scheme.*

Cost	*Nuclear power plant*	*Hydro-power plant*	*Steam power plant*
Capital per kW installed	*₹ 6000*	*₹ 4320*	*₹ 2160*
Interest	*10%*	*10%*	*12%*
Depreciation	*10%*	*8%*	*12%*
Operating cost per kWh	*12 paise*	*6 paise*	*18 paise*
Transmission and distribution cost/kWh	*0.24 paise*	*0.96 paise*	*0.24 paise*

Solution. *(i)* **Nuclear power plant :**

Capital cost $= 6000 \times (100 \times 10^3) =$ ₹ 60×10^7

Interest $= \frac{10}{100} \times 60 \times 10^7 =$ ₹ 6×10^7

Depreciation = ₹ 6×10^7

Annual fixed cost (interest + depreciation)

= ₹ 12×10^7

Energy generated per year

= Average load × (365 × 24)

= Load factor × maximum demand × (365 × 24)

$= 0.4 \times (100 \times 10^3) \times (365 \times 24)$

$= 350.4 \times 10^6$ kWh

Running cost per kWh

= Operating cost per kWh + transmission and distribution cost per kWh

= 12 + 0.24 = 12.24 p

∴ **Overall cost per kWh**

= Running cost/kWh + fixed cost/kWh

$$= 12.24 + \frac{12 \times 10^7}{350.4 \times 10^6} \times 100$$

= **46.48 p.** **(Ans.)**

(ii) **Hydro-electric power plant :**

Capital cost $= 4320 \times 100 \times 10^3 =$ ₹ 43.2×10^7

Interest $= \frac{10}{100} \times 43.2 \times 10^7 =$ ₹ 43.2×10^6

Depreciation $= \frac{8}{100} \times 43.2 \times 10^7 = 34.56 \times 10^6$

Annual fixed cost

= Interest + depreciation

= ₹ $(43.2 + 34.56) \times 10^6$

= ₹ 77.76×10^6

Running cost per kWh

= (Operation cost + transmission cost)

= (6 + 0.96) p = 6.96 p

Overall cost per kWh

= Running cost/kWh + annual fixed cost/kWh

$$= 6.96 + \frac{77.76 \times 10^6}{350.4 \times 10^6} \times 100$$

= 6.96 + 22.2 = **29.16 p.** **(Ans.)**

(iii) **Steam power plant :**

Capital cost = ₹ $2160 \times 100 \times 10^3$

= ₹ 21.6×10^7

Interest = ₹ $\frac{12}{100} \times 21.6 \times 10^7$

= ₹ 25.92×10^6

Depreciation = ₹ $\frac{12}{100} \times 21.6 \times 10^7$

= ₹ 25.92×10^6

Annual fixed cost = Interest + depreciation

= ₹ $2 \times 25.92 \times 10^6 =$ ₹ 51.84×10^6

Running cost/kWh = 18 + 0.24 = 18.24 p

Overall cost/kWh = Running cost/kWh + fixed cost/kWh

$$= 18.24 + \frac{51.84 \times 10^6}{350.4 \times 10^6} \times 100$$

= 18.24 + 14.79 = **33.03 p.** **(Ans.)**

From the above calculations it is concluded that overall cost/kWh is *minimum in case of hydropower plant*.

☞**Example 9.22.** *A power plant of 180 MW installed capacity has the following data :*

Capital cost = ₹ 2160/kW installed

Interest and depreciation = 12 per cent

Annual load factor = 0.6

Annual capacity factor = 0.5

Annual running charges = ₹ 36 × 10⁶

Energy consumed by power auxiliaries = 6 per cent

Calculate : (i) Reserve capacity

(ii) Generation capacity.

Solution. Load factor $= \frac{\text{Average load}}{\text{Maximum demand}}$

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

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

$$\frac{0.6}{0.5} = \frac{180}{\text{Maximum demand}}$$

∴ Maximum demand

$$= \frac{0.5 \times 180}{0.6} = 150 \text{ MW.}$$

(i) **Reserved capacity :**

Reserved capacity

= Installed/rated capacity – maximum demand

= 180 – 150 = **30 MW.** **(Ans.)**

(ii) **Generation cost :**

Average load = Load factor × maximum demand

= 0.6 × 150 = 90 MW

Energy generated per annum

$= 90 \times 10^3 \times (365 \times 24)$

$= 788.4 \times 10^6$ kWh

Energy consumed by auxiliaries

$$= \frac{6}{100} \times 788.4 \times 10^6 = 47.3 \times 10^6 \text{ kWh}$$

Net energy available

$= 788.4 \times 10^6 - 47.3 \times 10^6$

$= 741.1 \times 10^6$ kWh

Fixed cost of generation

= Interest + depreciation

$= ₹ \frac{12}{100} \times 2160 \times 180 \times 10^3 = ₹ 46.65 \times 10^6$

Total annual cost

= Running cost + fixed cost

$= 36 \times 10^6 + 46.65 \times 10^6 = ₹ 82.65 \times 10^6$

∴ *Generation cost*

$= \frac{82.65 \times 10^6}{741.1 \times 10^6} \times 100 =$ **11.1 p.** **(Ans.)**

Example 9.23. *A power station has the installed capacity of 180 MW. Calculate the cost of generation, other data pertaining to power station are given below :*

Capital cost $= ₹ 300 \times 10^6$

Rate of interest and depreciation

= 18 per cent

Annual cost of fuel oil, salaries and taxation

$= ₹ 36 \times 10^6$

Load factor = 0.4

Also calculate the saving in cost per kWh if the annual load factor is raised to 0.5.

Solution. Assuming maximum demand equal to the capacity of the power plant,

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

$$0.4 = \frac{\text{Average load}}{180}$$

∴ Average load = 0.4 × 180 = 72 MW

Energy generated per annum

$= 72 \times 10^3 \times (365 \times 24)$

$= 630.72 \times 10^6$ kWh

Fixed cost = Interest and depreciation on capital cost

$= \frac{18}{100} \times 300 \times 10^6 = ₹ 54 \times 10^6$

Running (operating cost)

= Cost of fuel oil, salaries and taxation

$= ₹ 36 \times 10^6$

Total annual cost

= Fixed cost + operating cost

$= ₹ (54 + 36) \times 10^6$

$= ₹ 90 \times 10^6$

∴ *Cost per kWh*

$= \frac{90 \times 10^6}{630.72 \times 10^6} \times 100$

= **14.27 p. per kWh.** **(Ans.)**

When the load factor is raised to 0.5 :

Average load = Load factor × maximum demand

= 0.5 × 180 = 90 MW

Energy produced per annum

$= 90 \times 10^3 \times 365 \times 24$

$= 788.4 \times 10^6$ kWh

Total annual cost will not change.

∴ Cost per kWh $= \frac{90 \times 10^6}{788.4 \times 10^6} \times 100$

= 11.41 p. per kWh

∴ *Saving in cost per kWh*

= 14.27 – 11.41

= **2.86 p.** **(Ans.)**

Example 9.24. *A 60 MW generating station has the following data :*

Capital cost $= ₹ 18 \times 10^6$

Annual taxation $= ₹ 0.48 \times 10^6$

Annual salaries and wages $= ₹ 1.44 \times 10^6$

Cost of coal = ₹ *72 per tonne*

Calorific value (C.V.) of coal = *23000 kJ/kg*

Rate of interest and depreciation

= 12 per cent

Plant heat rate = 138000 kJ/kWh at 100% capacity

Calculate the generating cost/kWh at 100% capacity factor.

Solution. Maximum demand

= 60 MW (= peak load)

Fixed cost = Interest and depreciation on capital cost

$= ₹ \frac{12}{100} \times 18 \times 10^6 = ₹ 2.16 \times 10^6$

Running cost = Annual salaries, wages and taxation

$= ₹ (1.44 + 0.48) 10^6$

$= ₹ 1.92 \times 10^6$

At 100% capacity factor :

Rated/installed capacity

= 60 MW

$$\text{Capacity factor} = \frac{\text{Average load}}{\text{Rated capacity}} = 1$$

or Average load = Rated capacity = 60 MW

Average energy produced per annum

$= 60 \times 10^3 \times (365 \times 24)$ kWh

$= 525.6 \times 10^6$ kWh

Total plant heat rate

$= 138000 \times 525.6 \times 10^6$ kJ

Weight of coal required per annum

$$= \frac{138000 \times 525.6 \times 10^6}{23000 \times 1000} \text{ tonnes}$$

$$= 3.15 \times 10^6 \text{ tonnes}$$

Cost of fuel $= ₹\ 72 \times 3.15 \times 10^6$

$= ₹\ 226.8 \times 10^6$

Total annual cost $= ₹\ (2.16 + 1.92 + 226.8) \times 10^6$

$= ₹\ 230.88 \times 10^6$

Generation cost $= \dfrac{230.88 \times 10^6}{525.6 \times 10^6} \times 100$

$=$ **43.93 p.** **(Ans.)**

ECONOMIC LOAD SHARING

Example 9.25. *An input-output curve of a 10 MW station is expressed as follows :*

$$I = 4 \times 10^6 (10 + 8L + 0.4L^2)$$

where I is in kJ/hour and L is in megawatts.

(i) Without plotting any curve find the load at which the maximum efficiency occurs.

(ii) Find the increase in input required to increase station output from 3 to 5 MW by means of the input-output curve and also by incremental rate curve.

Solution. (*i*) **Load at which maximum efficiency occurs :**

$$I = 4 \times 10^6 (10 + 8L + 0.4L^2)$$

or $$\frac{I}{L} = 4 \times 10^6 \left(\frac{10}{L} + 8 + 0.4L\right)$$

Efficiency $$= \frac{\text{Output}}{\text{Input}} = \frac{L}{I}$$

$\therefore$ Efficiency, $$\eta = \frac{1}{4 \times 10^6 \left(\dfrac{10}{L} + 8 + 0.4L\right)} \quad ...(i)$$

Now the *efficiency will be maximum* when $\left(\dfrac{10}{L} + 8 + 0.4L\right)$ is *minimum*

i.e., $$\frac{d}{dL}\left(\frac{10}{L} + 8 + 0.4L\right) = 0$$

$\therefore$ $$-\frac{10}{L^2} + 0.4 = 0$$

or $$L^2 = \frac{10}{0.4} = 25 \quad \text{or} \quad L = 5 \text{ MW}$$

Hence the load at which the maximum efficiency occurs = **5 MW.** **(Ans.)**

(*ii*) **Increase in input :**

(*a*) ***By input output curve :***

When load, L = 3 MW

Input, $I_3 = 4 \times 10^6 (10 + 8 \times 3 + 0.4 \times 3^2)$

$= 150.4 \times 10^6$ kJ/h

When load, $L = 5$ *MW*

Input, $I_5 = 4 \times 10^6 (10 + 8 \times 5 + 0.4 \times 5^2)$

$= 240 \times 10^6$ kJ/h

Increase in input required

$= I_5 - I_3$

$= (240 - 150.4) \times 10^6$

$=$ **89.6 × 10^6 kJ/h.** **(Ans.)**

(*b*) ***By incremental rate curve :***

When load varies from 3 to 5 MW, the incremental rate may be considered to be straight line and the average height of area under the curve between 3 MW and 5 MW would be

$$= \frac{3+5}{2} = 4 \text{ MW}$$

$$I = 4 \times 10^6 (10 + 8L + 0.4L^2)$$

Increment rate,

$$IR = \frac{dI}{dL} = 4 \times 10^6 (8 + 0.8L)$$

$\therefore$ $IR = 4 \times 10^6 (8 + 0.8 \times 4)$ when load

$= 4$ MW

$= 4 \times 10^6 (8 + 3.2) = 4 \times 10^6 \times 11.2$

Hence total increase in input

$= 4 \times 10^6 \times 11.2 (5 - 3)$

$=$ **89.6 × 10^6 kJ/h.** **(Ans.)**

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

Example 9.26. *The input-output curve of a 50 MW power station is given by :*

$$I = 4 \times 10^6 (8 + 8L + 0.4L^2) \text{ kJ/hour}$$

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

(i) 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.

(ii) 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. (*i*) **Heat input per day :**

Total energy generated by the plant during 24 hours

$= 20 \times 50 + 4 \times 0 = 1000$ MWh

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

$I_{50} = 4 \times 10^6 (8 + 8 \times 50 + 0.4 \times 50^2) \times 20$

$= 4 \times 1408 \times 20$ kJ during 20 hours

when the plant was running at *full load*.

Input at no load,

$I_0 = 4 \times 10^6 \times 8 \times 4$

$= 128 \times 10^6$ kJ during 4 hours when the plant was running at *no load*.

Total input to the plant during 24 hours

$= I_{50} + I_0 = 4 \times 10^6 \times 1408 \times 20 + 128 \times 10^6$

$= 10^6 (5632 \times 20 + 128)$

$= \mathbf{112768 \times 10^6}$ **kJ/day.** **(Ans.)**

***(ii)* Saving per kWh :**

Average heat supplied per kWh generated

$$= \frac{112768 \times 10^6}{1000 \times 10^3} = 112768 \text{ kJ/kWh}$$

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

$$\text{Average load} = \frac{1000}{24} = 41.67 \text{ MW}$$

Heat supplied during 24 hours in this case

$I_{50} = 4 \times 10^6 (8 + 8 \times 50 + 0.4 \times 41.67^2) \times 24$

$= 4 \times 10^6 (8 + 400 + 694.5) \times 24$

$= 4 \times 10^6 \times 1102.5 \times 24$ kJ/day

$= 105840 \times 10^6$ kJ/day

Net saving per day

$= 112768 \times 10^6 - 105840 \times 10^6$

$= 6928 \times 10^6$ kJ/day

∴ *Saving per kWh*

$$= \frac{6928 \times 10^6}{1000 \times 10^3} = \mathbf{6928 \text{ kJ/kWh.}} \quad \textbf{(Ans.)}$$

Example 9.27. *The incremental fuel costs for two generating units 1 and 2 of a power plant are given by the following equations :*

$$\frac{dF_1}{dP_1} = 0.07\, P_1 + 24$$

$$\frac{dF_2}{dP_2} = 0.075\, P_2 + 22$$

where F is fuel cost in rupees per hour and P is power output in MW. Determine :

(i) The economic loading of the two units when the total load supplied by the power plants is 180 MW.

(ii) The loss in fuel cost per hour if the load is equally shared by both units.

Solution. ***(i)* Economic loading of two units :**

$P_1 + P_2 = 180$ ...(Given) ...(*i*)

The condition required for economic loading is given by :

$$\frac{dF_1}{dP_1} = \frac{dF_2}{dP_2}$$

∴ $0.07\, P_1 + 24 = 0.075\, P_2 + 22$ ...(*ii*)

Substituting the value of P_2 (= $180 - P_1$) from (*i*) in (*ii*), we get

$0.07\, P_1 + 24 = 0.075\,(180 - P_1) + 22$

or $0.07\, P_1 + 24 = 13.5 - 0.075\, P_1 + 22$

or $0.145\, P_1 = 11.5$

or, $P_1 = \dfrac{11.5}{0.145} = \mathbf{79.3}$ **MW.** **(Ans.)**

and, $P_2 = 180 - 79.3 = \mathbf{100.7}$ **MW.** **(Ans.)**

***(ii)* Loss in fuel cost :**

If the load is equally shared by both the units $\left(\text{supplying } \dfrac{180}{2} = 90 \text{ MW each}\right)$, then the increase in cost of fuel for *unit 1*

$$= \int_{79.3}^{90} (0.07\, P_1 + 24)\, dP_1$$

$$= \left[\frac{0.07\, P_1^2}{2} + 24 P_1\right]_{79.3}^{90}$$

$= 0.035\,(90^2 - 79.3^2) + 24\,(90 - 79.3)$

$= 63.4 + 256.8 =$ ₹ 320.2/hour

Increase in cost of fuel for *unit 2*

$$= \int_{100.7}^{90} (0.075\, P_2 + 22)\, dP_2$$

$$= \left[\frac{0.075 P_2^2}{2} + 22 P_2\right]_{100.7}^{90}$$

$$= \frac{0.075}{2}\,(90^2 - 100.7^2) + 22\,(90 - 100.7)$$

$= -76.5 - 235.4 =$ ₹ -311.9/hour

This indicates that the cost of fuel for unit 2 **decreases**.

Net increase in cost (or *loss in fuel cost*) due to departure from economic distribution of load

$= 320.2 - 311.9 =$ **₹ 8.3/hour.** **(Ans.)**

Example 9.28. *Two steam turbines each of 30 MW capacity take a load 45 MW. The steam consumption rates in kg per hour for both turbines are given by the following equations :*

$$S_1 = 2400 + 12L_1 - 0.00012\, L_1^2$$

$$S_2 = 1200 + 8.4L_2 - 0.00006\, L_2^2$$

L represents the load in kW and S represents the steam consumption per hour. Find the most economical loading when the load taken by both units is 45 MW.

Solution. $L_1 + L_2 = 45$ MW = 45000 kW ...(*i*)

For the most economical loading, the required condition is

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

∴ $12 - 2 \times 0.00012\, L_1 = 8.4 - 2 \times 0.00006\, L_2$

$12 - 0.00024\, L_1 = 8.4 - 0.00012\, L_2$ ...(*ii*)

Substituting the value of L_2 (= $45000 - L_1$) from (*i*) in (*ii*), we get

$12 - 0.00024\, L_1 = 8.4 - 0.00012\,(45000 - L_1)$

$12 - 0.00024\, L_1 = 8.4 - 5.4 + 0.00012\, L_1$

$0.00036\, L_1 = 9$

$$\therefore \qquad L_1 = \frac{9}{0.00036} = \textbf{25000 kW}$$

or 25 MW. (Ans.)

and $$L_2 = 45000 - 25000 = \textbf{20000 kW}$$

or 20 MW. (Ans.)

TARIFF

Example 9.29. *Two electrical units used for same purpose are compared for their economical working :*

(i) Cost of Unit-1 is ₹ 6000 and it takes 120 kW.

(ii) Cost of Unit-2 is ₹ 16800 and it takes 72 kW.

Each of them has a useful life of 40000 hours.

Which unit will prove economical if the energy is charged at ₹ 96 per kW of maximum demand per year and 6 p. per kWh ?

Assume both units run at full load.

Solution. (*i*) **Unit-1 :**

Capital cost per hour $= \frac{6000}{40000} =$ ₹ 0.15

Maximum demand = 120 kW

Charge for maximum demand per hour

$$= \frac{120 \times 96}{(365 \times 24)} = ₹\ 1.315$$

Energy charge per hour = Maximum demand × one hour × charge per kWh

$$= 120 \times 1 \times \frac{6}{100} = ₹\ 7.2$$

∴ Total charges per hour for operation of Unit-1

= 0.15 + 1.135 + 7.2 = ₹ 8.485

(*ii*) **Unit-2 :**

Capital cost per hour

$$= \frac{16800}{40000} = ₹\ 0.42.$$

Charge for maximum demand per hour

$$= \frac{72 \times 96}{365 \times 24} = ₹\ 0.789$$

Energy charge per hour

$$= 72 \times 1 \times \frac{6}{100} = ₹\ 4.32$$

Total charges per hour for the operation of Unit-2

= 0.42 + 0.789 + 4.32 = ₹ 5.529

The charges of operation for the Unit-2 per hour are less than the charges of operation for the Unit-1, therefore *Unit-2 is more economical* in this case. **(Ans.)**

Example 9.30. *The monthly electricity consumption of a residence can be approximated as under :*

Light load : 6 tube lights 40 watts each working for 4 hours daily

Fan load : 6 fans 100 watts each working for 6 hours daily

Refrigerator load : 2 kWh daily

Miscellaneous load : 2 kW for 2 hours daily

Find the monthly bill at the following tariff :

First 20 units	*₹ 0.50/kWh*
Next 30 units	*₹ 0.40/kWh*
Remaining units	*₹ 0.30/kWh*
Constant charge	*₹ 2.50 per month*

Discount for prompt payment = 5 per cent.

Solution. Total energy consumption in 30 days

$$= (6 \times 40 \times 4 \times 30 + 6 \times 100 \times 6 \times 30) \times \frac{1}{1000} + 2 \times 30 + 2 \times 2 \times 30$$

$$= (28800 + 108000) \times \frac{1}{1000} + 60 + 120$$

= 316.8 kWh per month

The monthly bill

= ₹ [(20 × 0.5 + 30 × 0.4 + 266.8 × 0.3) + 2.5]

= ₹ [(10 + 12 + 80.04) + 2.5] = ₹ 104.54

$$\left[\because \text{ Remaining units per month } = 316.8 - 20 - 30 = 266.8\right]$$

Net monthly bill if the payment is made promptly

= 104.54 × 0.9 = ₹ **94.08. (Ans.)**

Example 9.31. *An industrial undertaking has a connected load of 220 kW. The maximum demand is 180 kW. On an average each machine works for 60% time. Find the yearly expenditure on electricity if the tariff is :*

₹ 1200 + ₹ 120 per kW of maximum demand per year + ₹ 0.15 per kWh.

Solution. Energy consumption in one year

= 180 × 0.6 × (365 × 24) = 946080 kWh

Total electricity bill

= ₹ (1200 + 120 × 180 + 0.15 × 946080)

= ₹ **164712. (Ans.)**

☞**Example 9.32.** *A Hopkinson demand rate is quoted as follows :*

Demand rates :

First 1 kW of maximum demand
= ₹ 6/kW/month

Next 4 kW of maximum demand
= ₹ 5/kW/month

Excess 5 kW of maximum demand
= ₹ 4/kW/month

Energy rates :

First 50 kWh = 7 paise/kWh
Next 50 kWh = 5 paise/kWh
Next 200 kWh = 4 paise/kWh
Next 400 kWh = 3 paise/kWh
Excess over 700 kWh = 2 paise/kWh.

Determine : (i) The monthly bill for a total consumption of 2000 kWh and a maximum demand of 15 kW. Also find out the unit energy cost.

(ii) Lowest possible bill for a month and a corresponding unit energy cost.

Solution. *(i)* **Monthly bill and energy cost :**

Demand charges per month

$= ₹\ (1 \times 6 + 4 \times 5 + 10 \times 4) = ₹\ 66$

Energy charge $= ₹\ [50 \times 7 + 50 \times 5 + 200 \times 4 + 400 \times 3 + 1300 \times 2] \times \frac{1}{100}$

$= ₹\ (350 + 250 + 800 + 1200 + 2600) \times \frac{1}{100} = ₹\ 52$

∴ *Monthly bill* $= 66 + 52 =$ **₹ 118. (Ans.)**

Average unit energy cost

$= \frac{118}{2000} \times 100$

= **5.9 paise/kWh. (Ans.)**

(ii) **Lowest possible bill :**

The lowest possible bill will occur when average load

= Maximum load or at 100% load factor

∴ Maximum load

$= \text{Average load} = \frac{2000}{30 \times 24} = 2.77 \text{ kW}$

∴ Demand charges

$= ₹\ (6 + 1.77 \times 5) = ₹\ 14.85$

Energy charges will be same

= ₹ 52

∴ *Minimum monthly bill*

$= 14.85 + 52 =$ **₹ 66.85. (Ans.)**

Unity energy cost for this condition

$= \frac{66.85}{2000} \times 100 =$ **3.34 paise/kWh. (Ans.)**

TARIFF AND COST ANALYSIS

☞**Example 9.33.** *A new factory requires a maximum demand of 700 kW and load factor of 25%. The following two suppliers are available :*

(i) Public supply tariff is ₹ 48 per kW of maximum demand plus 2.4 p. per kWh.

Capital cost	*= ₹ 84000*
Interest and depreciation	*= 10 per cent*

(ii) Private oil engine generating station :

Capital cost	*= ₹ 300000*
Fuel consumption	*= 3 N/kWh*
Cost of fuel	*= ₹ 8.4 per kN*
Wages	*= 0.48 p/kWh*
Maintenance cost	*= 0.36 p/kWh*
Interest and depreciation	*= 15 per cent.*

Find which supply will be more economical ?

Solution. Load factor $= \frac{\text{Average load}}{\text{Maximum demand}}$

∴ Average load

= Load factor × maximum demand

$= 0.25 \times 700 = 175$ kW

Energy consumed per year

$= 175 \times (365 \times 24) = 1.533 \times 10^6$ kWh.

(i) **Public supply :**

Maximum demand charges per year

$= 48 \times 700 = ₹\ 33600$

Energy charge per year

$= \frac{2.4}{100} \times 1.533 \times 10^6 = ₹\ 36792$

Interest and depreciation

$= \frac{10}{100} \times 84000 = ₹\ 8400$

Total cost $= ₹\ (33600 + 36792 + 8400) = ₹\ 78792$

∴ *Energy cost per kWh*

$= \frac{78792}{1.533 \times 10^6} \times 100 =$ **5.14 p.**

(ii) **Private oil engine generating station :**

Fuel consumption

$= \frac{3 \times 1.533 \times 10^6}{1000} = 4599$ kN

Cost of fuel $= 4599 \times 8.4 = ₹\ 38631$

Cost of wages and maintenance

$= \left(\frac{0.48 + 0.36}{100}\right) \times 1.533 \times 10^6 = ₹\ 12877$

Interest and depreciation

$= \frac{15}{100} \times 300000 = ₹\ 45000$

Total cost

$= ₹\ (38631 + 12877 + 45000) = ₹\ 96508$

Energy cost per kWh

$= \frac{96508}{1.533 \times 10^6} \times 100 =$ **6.29 p.**

As the energy cost per kWh for oil engine is less than the public supply, the oil engine generation is more preferable. **(Ans.)**

☞**Example 9.34.** *A load having a maximum demand of 100 MW and a load factor of 0.4 may be supplied by one of the following schemes :*

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

(ii) A steam station in conjunction with pump storage plant which is capable of supplying 130 × 10^6 kWh energy per year with a maximum output of 40 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

= ₹ 2000/kW of installed capacity

Capital cost of pump storage plant

= ₹ 1300/kW of installed capacity

Operating cost of steam plant

= 6 p./kWh

Operating cost of pump storage plant

= 0.5 p./kWh

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

Solution. (*i*) **Steam station :**

Capital cost $= 100 \times 10^3 \times 2000 =$ ₹ 200×10^6

Interest and depreciation

$$= \frac{12}{100} \times 200 \times 10^6 = \text{₹ } 24 \times 10^6$$

Average load

= Load factor × maximum demand

$= 0.4 \times 100 \times 10^3 = 40000$ kW

Energy supplied per year

= Average load × (365 × 24)

$= 40000 \times 365 \times 24 = 350.4 \times 10^6$ kWh

∴ Interest and depreciation charges *per unit of energy*

$$= \frac{24 \times 10^6}{350.4 \times 10^6} \times 100 = 6.85 \text{ p/kWh}$$

∴ *Total cost per unit*

= 6 + 6.85 = **12.85 p/kWh.** **(Ans.)**

(*ii*) **Steam station in conjunction with pump-storage plant :**

The load supplied by the steam plant

= 100 – 40 = 60 MW

∴ Capital cost of steam plant

$= 60 \times 1000 \times 2000 =$ ₹ 120×10^6

Capital cost of pump storage plant

$= 40 \times 1000 \times 1300 =$ ₹ 52×10^6

∴ Total capital cost of combined station

$= 120 \times 10^6 + 52 \times 10^6 =$ ₹ 172×10^6

Interest and depreciation charges on capital investment

$$= \frac{12}{100} \times 172 \times 10^6 = \text{₹ } 20.64 \times 10^6$$

∴ Operating cost of pump storage plant

$$= \frac{0.5}{100} \times 130 \times 10^6 = \text{₹ } 0.65 \times 10^6$$

The energy units supplied by steam station

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

$= 350.4 \times 10^6 - 130 \times 10^6$

$= 220.4 \times 10^6$ kWh

Operating cost of the steam station

$$= \frac{6}{100} \times 220.4 \times 10^6 = \text{₹ } 13.22 \times 10^6$$

Total cost per year

= ₹ $(20.64 \times 10^6 + 0.65 \times 10^6 + 13.22 \times 10^6)$

= ₹ 34.51×10^6

Total cost per unit

$$= \frac{34.51 \times 10^6}{350.4 \times 10^6} \times 100$$

= **9.85 p/kWh.** **(Ans.)**

Note. If the above example is repeated with a load factor of 0.7 it will be observed from the results that the *cost of generation becomes less with higher load factor irrespective of the type of the plant.*

Example 9.35. *The following data relate to a 2000 kW diesel power station :*

The peak load on the plant = 1500 kW

Load factor = 0.4

Capital cost per kW installed = ₹ 1200

Annual costs = 15 per cent of capital

Annual operating costs = ₹ 50000

Annual maintenance costs :

(*i*) *Fixed = ₹ 9000*

(*ii*) *Variable = ₹ 18000*

Cost of fuel = ₹ 0.45 per kg

Cost of lubricating oil = ₹ 1.3 per kg

C.V. of fuel = 41800 kJ/kg

Consumption of fuel = 0.45 kg/kWh

Consumption of lubricating oil = 0.002 kg/kWh

Determine the following :

(*i*) *The annual energy generated.*

(*ii*) *The cost of generation per kWh.*

Solution. Capital cost of the plant

$= 2000 \times 1200 =$ ₹ 2.4×10^6 per year

Interest on capital

$$= \frac{15}{100} \times 2.4 \times 10^6$$

= ₹ 0.36×10^6 per year.

(*i*) **Annual energy generated**

= Load factor × maximum demand × (365 × 24)

$= 0.4 \times 1500 \times 365 \times 24 =$ **5.256×10^6 kWh.** **(Ans.)**

(*ii*) Cost of generation :

Fuel consumption $= 0.45 \times 5.256 \times 10^6$
$= 2.365 \times 10^6$ kg per year

Cost of fuel $=$ ₹ $0.45 \times 2.365 \times 10^6$
$=$ ₹ 1.064×10^6 per year

Lubricant consumption $= 0.002 \times 5.256 \times 10^6$
$= 10512$ kg per year

Cost of lubricating oil $= 1.3 \times 10512$
$=$ ₹ 13665 per year

Total fixed cost = Interest + maintenance (fixed)
$= 0.36 \times 10^6 + 9000$
$=$ ₹ 369000 per year

Total running or variable costs
= Fuel cost + lubricant cost
+ maintenance (running)
+ annual operating costs
$= 1.064 \times 10^6 + 13665 + 18000 + 50000$
$=$ ₹ 1145665 per year

Total cost = Fixed cost + running cost
$= 369000 + 1145665 =$ ₹ 1514665

Cost of generation

$$= \frac{1514665}{5.256 \times 10^6} \times 100$$

= 28.8 paise/kWh. (Ans.)

☞**Example 9.36.** *The annual costs of operating a 15 MW thermal plant are given below :*

Capital cost of plant
= ₹ 1500/kW

Interest, insurance and depreciation
= 10 per cent of plant cost

Capital cost of primary and secondary distribution
$= ₹ 20 \times 10^6$

Interest, insurance and depreciation on the capital cost of primary and secondary distribution
= 5% the capital cost

Plant maintenance cost
$= ₹ 100 \times 10^3$ *per year*

Maintenance cost of primary and secondary equipment
$= ₹ 2.2 \times 10^5$ *per year*

Salaries and wages
$= ₹ 6.5 \times 10^5$ *per year*

Consumption of coal
$= 40 \times 10^4$ *kN per year*

Cost of coal *= ₹ 9 per kN*

Dividend to stockholders
$= ₹ 1.5 \times 10^6$ *per year*

Energy loss in transmission
= 10 per cent

Diversity factor *= 1.5*

Load factor *= 0.75*

Maximum demand
= 12 MW

(*i*) *Devise a two-part tariff.*

(*ii*) *Find the average cost per kWh.*

Solution. (*i*) **Two-part tariff :**

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

∴ Average load
= Load factor × maximum demand
$= 0.75 \times 12 \times 10^3 = 9000$ kW

Energy generated per year
$= 9000 \times (365 \times 24) = 78.84 \times 10^6$ kWh

Cost of the plant
$= 15 \times 10^3 \times 1500 =$ ₹ 22.5×10^6

Interest, insurance and depreciation charges of the plant

$$= \frac{10}{100} \times 22.5 \times 10^6 = ₹\ 2.25 \times 10^6$$

Interest, insurance and depreciation charges of primary and secondary equipments

$$= \frac{5}{100} \times 20 \times 10^6 = ₹\ 1.0 \times 10^6$$

Total fixed cost = Insurance, interest and depreciation costs + dividend to stock-holders
$=$ ₹ $(2.25 \times 10^6 + 1.5 \times 10^6) =$ ₹ 3.75×10^6

Sum of individual maximum demand
= Maximum demand × diversity factor
$= 12 \times 10^3 \times 1.5 = 18000$ kW

∴ *Fixed charges per kW*

$$= \frac{3.75 \times 10^6}{18000} = ₹\ \mathbf{208.3.}$$

Total variable charges
= All maintenance costs
+ salaries and wages + fuel cost
$= (100 \times 10^3 + 2.2 \times 10^5) + 6.5 \times 10^5 + 40 \times 10^4 \times 9$
$= (1 \times 10^5 + 2.2 \times 10^5) + 6.5 \times 10^5 + 36 \times 10^5$
$=$ ₹ 45.7×10^5 or ₹ 4.57×10^6

Energy transmitted
= Energy generated × transmission efficiency
$$= 78.84 \times 10^6 \times \left(\frac{100 - \text{energy loss in transmission}}{100}\right)$$

$$= 78.84 \times 10^6 \times \frac{90}{100} = 70.956 \times 10^6 \text{ kWh}$$

∴ *Charges for energy consumption*

$$= \frac{4.57 \times 10^6}{70.956 \times 10^6} \times 100 = \textbf{6.44 paise/kWh.}$$

∴ *Two-part tariff*

= **₹ 208.3/kW + 6.44 paise/kWh.** **(Ans.)**

(*ii*) Average cost per kWh :

Total charges = Fixed charges + variable charges

$= 3.75 \times 10^6 + 4.57 \times 10^6$

$= ₹\ 8.32 \times 10^6$

Average cost of supply

$$= \frac{8.32 \times 10^6}{70.956 \times 10^6} \times 100$$

= **11.72 paise/kWh.** **(Ans.)**

Example 9.37. *A 10 MW thermal power plant has the following data :*

Peak load = *8 MW*

Plant annual load factor

= *0.72*

Cost of the plant = *₹800/kW installed capacity*

Interest, insurance and depreciation

= *10 per cent of the capital cost*

Cost of transmission and distribution system

= *₹350 × 10³*

Interest, depreciation on distribution system

= *5 per cent*

Operating cost = *₹350 × 10³ per year*

Cost of coal = *₹6 per kN*

Plant maintenance cost

= *₹30000/year (fixed)*

= *₹40000/year (running)*

Coal used = *250000 kN/year*

Assume transmission and distribution costs are to be charged to generation

(i) Devise a two-part tariff.

(ii) Average cost of generation in paise/kWh.

Solution. **(*i*) Two-part tariff :**

S. No.	Items	Fixed cost per year (in ₹)	Running cost per year (in ₹)
1.	Interest, depreciation etc. of the plant	$\frac{10}{100} \times 10000 \times 800$ $= ₹\ 800 \times 10^3$	–
2.	Interest, depreciation etc. of the transmission and distribution	$\frac{5}{100} \times 350 \times 10^3$ $= 17.5 \times 10^3$	–
3.	Annual cost of coal	–	250000×6 $= 1500 \times 10^3$
4.	Operating cost	–	$= 350 \times 10^3$
5.	Plant maintenance cost	$= 30 \times 10^3$	$= 40 \times 10^3$
	Total cost	847.5×10^3	1890×10^3

∴ Grand total cost

= Fixed cost + running cost

$= 847.5 \times 10^3 + 1890 \times 10^3$

$= ₹\ 2737.5 \times 10^3$

Energy generated/year

= Average load × (365 × 24)

= (Peak load × load factor) × (365 × 24)

$= (8 \times 10^3 \times 0.72) \times (365 \times 24)$

$= 50.46 \times 10^6$ kWh

∴ *Two-part tariff*

$$= \frac{\text{Fixed cost}}{\text{Maximum load}} + \frac{\text{Running cost}}{\text{Energy generated}}$$

$$= \frac{847.5 \times 10^3}{8 \times 10^3} + \frac{1890 \times 10^3}{50.46 \times 10^6} \times 100$$

= **₹ 105.9/kW + paise 3.74/kWh.** **(Ans.)**

(*ii*) Average cost generation in paise/kWh :

Average generation cost

$$= \frac{\text{Grand total cost}}{\text{Energy generated}}$$

$$= \frac{2737.5 \times 10^3}{50.46 \times 10^6} \times 100$$

= **5.42 paise/kWh.** **(Ans.)**

Example 9.38. *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 : *₹(40/kW + 0.06/kWh)*

Steam : *₹(160/kW + 0.015/kWh).*

Solution. Let P = Maximum load in kW, and

x = Load factor (same for both the stations).

Then, Average load

$$= P \times x$$

Cost of diesel station,

$$C_{\text{diesel}} = 40\,P + 0.06 \times P \times x \times (365 \times 24)$$

Cost of steam station,

$$C_{\text{steam}} = 160\,P + 0.015 \times P \times x \times (365 \times 24)$$

As given in the problem,

Unit energy cost (diesel station) = Unit energy cost (steam station)

$$\therefore \quad \frac{40\,P + 0.06\,Px \times (365 \times 24)}{Px \times (365 \times 24)} = \frac{160\,P + 0.015\,Px \times (365 \times 24)}{Px \times (365 \times 24)}$$

$$\therefore \quad 40\,P + 0.06\,Px \times 8760 = 160\,P + 0.015\,Px \times 8760$$

or $$40\,P + 525.6\,Px = 160\,P + 131.4\,Px$$

or $$120\,P = 394.2\,Px$$

or $$x = \frac{120}{394.2} = 0.3$$

i.e., Load factor = **0.3.** **(Ans.)**

Example 9.39. *A motor of 25 H.P. connected to a condensate pump has been burnt beyond economical repairs. Two alternatives have been proposed to replace it by :*

	Cost	η at full load	η at half load
Motor A :	*₹ 5000*	*90%*	*85%*
Motor B :	*₹ 3500*	*86%*	*80%*

The life of each motor is 20 years and its salvage value is 12 per cent of the initial cost. The rate of interest is 5 per cent annually. The motor operates at full load for 30% of time and at half load for the remaining period. The annual maintenance cost of motor A is ₹ 400 and that of motor B is ₹ 200. The energy rate is 12 paise/kWh.

Which motor will be economical ?

Solution. Motor A :

Salvage value $= \dfrac{12}{100} \times 5000 = ₹\ 600$

Depreciation $= \dfrac{5000 - 600}{20} = ₹\ 220/\text{year}$

Interest $= \dfrac{5}{100} \times 5000 = ₹\ 250/\text{year}$

Maintenance = ₹ 400

Energy given to motor

$$= \frac{\text{Load on motor} \times \text{time in hours}}{\text{Efficiency of the motor}}$$

$\therefore$ Energy cost

$$= \left[\left(25 \times 0.7355 \times (365 \times 24) \times \frac{30}{100} \times \frac{1}{0.9}\right) + \left((25 \times 0.7355) \times \frac{1}{2} \times (365 \times 24) \times \frac{70}{100} \times \frac{1}{0.85}\right)\right] \times \frac{12}{100}$$

$$= (53691.5 + 66324.8) \times \frac{12}{100}$$

$$= ₹\ 14402/\text{year}$$

$\therefore$ *Total cost of motor A*

$= 220 + 250 + 400 + 14402 =$ **₹ 15272/year.**

Motor B :

Salvage value $= \dfrac{12}{100} \times 3500 = ₹\ 420$

Depreciation $= \dfrac{3500 - 420}{20} = ₹\ 154$

Interest $= \dfrac{5}{100} \times 3500 = ₹\ 175$

Maintenance = ₹ 200

Energy cost

$$= \left[\left(25 \times 0.7355 \times (365 \times 24) \times \frac{30}{100} \times \frac{1}{0.86}\right) + \left(25 \times 0.7355 \times \frac{1}{2} \times (365 \times 24) \times \frac{70}{100} \times \frac{1}{0.8}\right)\right] \times \frac{12}{100}$$

$$= (56188.8 + 70470) \times \frac{12}{100} = ₹\ 15199$$

Total cost of motor B

$= 154 + 175 + 200 + 15199 =$ **₹ 15728/year.**

Hence motor A is economical since its annual cost is less than motor B.

☞**Example 9.40.** *The following proposals are under consideration for an industry which has a maximum demand of 45 MW and a load factor of 0.45 :*

(i) A steam plant having an initial cost of ₹ 1200/kW and maintenance cost of 2.4 paise/kWh. The coal of C.V. of 2550 kJ/N is used. The overall efficiency of the plant is 24 per cent.

(ii) An hydro-plant having a capital cost of ₹ 3600/kW and a running cost of 0.6 paise/kWh.

Assuming interest and depreciation rate of 10 per cent for steam plant and 8 per cent for hydro-plant, determine the price of coal above which steam station is uneconomical.

Solution. Energy required per year

$$= \text{Peak load} \times \text{load factor} \times (365 \times 24)$$

$$= 45 \times 10^3 \times 0.45 \times (365 \times 24)$$

$$= 177.39 \times 10^6\ \text{kWh/year}$$

(i) **Steam plant :**

Interest and depreciation

$$= \frac{10}{100} \times (45 \times 10^3) \times 1200 = ₹\ 5.4 \times 10^6$$

Maintenance cost

$$= \frac{2.4}{100} \times 177.39 \times 10^6 = ₹\ 4.257 \times 10^6$$

Let W_{coal} = Weight of coal in kN used/year, and

x = Cost of coal in rupees per kN

$\therefore \quad W_{coal} \times 10^3 \times \text{C.V.} \times \eta_{overall}$

$= 177.39 \times 10^6 \times 3.6 \times 10^3$

$(\because \quad 1 \text{ kWh} = 3.6 \times 10^3 \text{ kJ})$

or $$W_{coal} = \frac{177.39 \times 10^6 \times (3.6 \times 10^3)}{10^3 \times 2550 \times 0.24}$$

$= 1.043 \times 10^6$ kN/year

Now, total cost of steam plant

= Interest + maintenance cost + fuel cost

$= 5.4 \times 10^6 + 4.257 \times 10^6 + 1.043 \times 10^6 \times x$ ...(1)

(ii) **Hydel plant :**

Interest and depreciation

$$= 45 \times 10^3 \times 3600 \times \frac{8}{100} = ₹\ 12.96 \times 10^6$$

Running cost

$$= \frac{0.6}{100} \times 177.39 \times 10^6 = ₹\ 1.064 \times 10^6$$

Total cost of hydel plant

$= 12.96 \times 10^6 + 1.064 \times 10^6$

$= ₹\ 14.024 \times 10^6$ ...(2)

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

$\therefore$ Equating the values of (1) and (2), we get

$5.4 \times 10^6 + 4.257 \times 10^6 + 1.043 \times 10^6 \times x$

$= 14.024 \times 10^6$

or $5.4 + 4.257 + 1.043\,x$

$= 14.024$ (Dividing both sides by 10^6)

$$\therefore \quad x = \frac{14.024 - 5.4 - 4.257}{1.043} = ₹\ 4.19 \text{ per kN}$$

Hence price coal above which steam station is uneconomical = **₹ 4.19 per kN.** **(Ans.)**

Example 9.41. *An industrial consumer has a choice between low and high voltage supply available at the following rates :*

High voltage : ₹ 50/kW per year + paise 4/kWh

Low voltage : ₹ 55/kW per year + paise 5/kWh

In order to have high voltage supply, consumer has to install his own transformer which costs ₹ 110/kW. The losses in the transformer are 4 per cent of full load. Determine the number of working hours per week above which the high voltage supply will be economical.

Assume : interest and depreciation 12 per cent of capital, working weeks per year 50 and load of consumer as 1.5 MW.

Solution. Consumer load

= 1.5 MW = 1500 kW

Required rating of transformer

$$= \frac{1500}{(1 - 0.4)} = 1562 \text{ kW}$$

Cost of the transformer to the consumer

$= 1562 \times 110 = ₹\ 171820$

Annual interest and depreciation

$$= \frac{12}{100} \times 171820 = ₹\ 20618$$

Let the number of hours for which power is required by the consumer = x hours/week

$\therefore$ Number of hours for which power is used during the year = $50x$ hours

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

$= 1500 \times 50x = 75000x$ kWh/year

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

$= 1562 \times 50x = 78100x$ kWh/year

Total cost from low voltage supply in rupees

$$= 1500 \times 55 + 75000x \times \frac{5}{100}$$

$= 82500 + 3750x$ ...(1)

Total cost from high voltage supply in rupees

$$= 1562 \times 50 + 78100x \times \frac{4}{100} + 20618$$

$= 98718 + 3124x$ ...(2)

It both the systems cost the same to the consumer, then equating (1) and (2), we get

$82500 + 3750x = 98718 + 3124x$

i.e., $$x = \frac{98718 - 82500}{(3750 - 3124)} = \frac{16218}{626} = 25.9 \text{ hours.}$$

Hence the number of working hours above which the high voltage supply will be economical

= **25.9 hours.** **(Ans.)**

ADDITIONAL/TYPICAL EXAMPLES

Example 9.42. *A diesel electric station has 4-generating sets, each of 500 kW and 1 of 400 kW capacity.*

The other data is given below :

Maximum demand	*1500 kW*
Load factor	*0.5*
Capital cost	*₹ 10000/kW*
Annual cost (interest + depreciation + insurances and taxes)	*16% of capital cost*
Annual maintenance cost	*₹ 45000*
Operation cost	*₹ 8000*
Fuel used	*0.45 kg/kWh*
Cost of fuel	*₹ 8/kg*
Lubricating oil used	*0.0024 kg/kWh*
Cost of lubricating oil	*₹ 45/kg*
Calorific value of fuel used	*41000 kJ/kg*
Generator efficiency	*90%*

Determine the following :

(i) The rating of diesel engine,

(ii) Energy produced per year,

(iii) Cost of generation, ₹/kWh, and

(iv) Overall efficiency of the plant. **(N.U.)**

Solution. (*i*) **The rating of diesel engine :**

Rating of first 3-sets

$$= \frac{500}{0.9} = \textbf{555 kW.} \quad \textbf{(Ans.)}$$

Rating of last set

$$= \frac{400}{0.9} = \textbf{445 kW.} \quad \textbf{(Ans.)}$$

(*ii*) **Energy produced per year :**

Average demand

= Maximum demand × load factor

= 1500 × 0.5 = 750 kW

∴ Energy produced per year

$$= 750 \times 8760 = \mathbf{6.57 \times 10^6\ kWh.} \quad \textbf{(Ans.)}$$

(*iii*) **Cost of generation, ₹/kWh :**

Fixed cost per year :

Capital cost $= (3 \times 500 + 1 \times 400) \times 10000$

$= ₹\ 1.9 \times 10^7$

$$\text{Annual fixed cost} = \frac{16}{100} \times 1.9 \times 10^7 = ₹\ 0.304 \times 10^7$$

Maintenance cost $= ₹\ 45000 = ₹\ 0.0045 \times 10^7$

Total fixed cost $= ₹\ (0.304 + 0.0045) \times 10^7$

$= ₹\ 0.3085 \times 10^7$

Variable cost per year :

Fuel cost $= (6.57 \times 10^6 \times 0.45) \times 8$

$= ₹\ 23.65 \times 10^6$

Cost of lubricating oil

$= (6.57 \times 10^6 \times 0.0024) \times 45$

$= ₹\ 0.71 \times 10^6$

Total variable cost per year

$= (23.65 + 0.71) \times 10^6 = ₹\ 24.36 \times 10^6$

Total cost = Fixed cost + variable cost

$= 3.085 \times 10^6 + 24.36 \times 10^6$

$= ₹\ 27.44 \times 10^6$

∴ **Cost per kWh generated**

$$= \frac{\text{Total cost}}{\text{Energy generated per year}}$$

$$= \frac{27.44 \times 10^6}{6.57 \times 10^6} \simeq ₹\ \mathbf{4.18.} \quad \textbf{(Ans.)}$$

(*iv*) **Overall efficiency of the plant, $\eta_{overall}$:**

$$\eta_{overall} = \frac{\text{Output}}{\text{Input}} = \frac{6.57 \times 10^6 \times 3600\ (\text{kJ})}{6.57 \times 10^6 \times 0.45 \times 41000\ (\text{kJ})}$$

$$= 0.195 \quad \text{or} \quad \mathbf{19.5\%.} \quad \textbf{(Ans.)}$$

Example 9.43. *A load curve of a factory follows a parabola and it works for 8 hours a day from 10 A.M. to 6 P.M. The maximum and minimum loads of the factory are $\sqrt{3}$ MW and 1 MW. The capacity of the diesel power plant supplying the power to the factory is 2 MW. Determine the following :*

(i) Load factor and capacity factor of the plant supplying power to the factory.

(ii) Energy consumption of the factory per month assuming it works for 26 days per month and 8 hours per day.

(iii) Electrical charges to be paid by the factory if the charges are ₹ 60/kW for maximum load during a day and ₹ 2.75/kWh.

The time at 6 A.M. may be taken as zero. **(M.U.)**

Solution. *Given* : Working hours per day = 8 (10 A.M. to 6 P.M.) ; Maximum load = $\sqrt{3}$ MW ; Minimum load = 1 MW ; Capacity of diesel power plant = 2 MW ; Tariff : ₹ 60/kW (maximum load) ; ₹ 2.75/kWh.

The load curve is shown in Fig. 9.18.

The load curve is given by :

$$y^2 = ax,$$

where x and y represent hours and MW respectively.

The boundary conditions are :

At $x = 0, y = 0$; At $x = 4, y = 1$

$$\therefore \quad 1 = a \times 4 \quad \text{or} \quad a = \frac{1}{4}$$

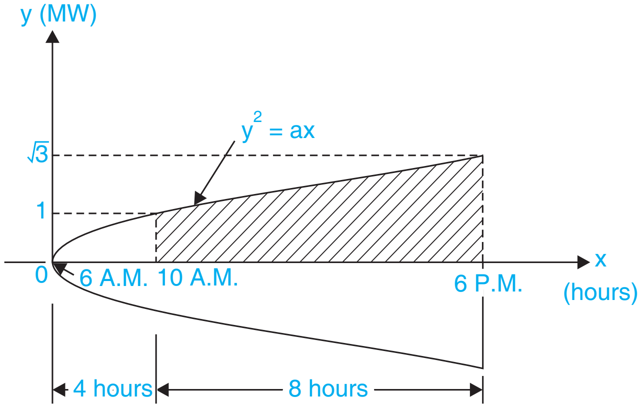


Fig. 9.18

$$\therefore \qquad y^2 = \frac{x}{4} \quad \text{or} \quad y = \frac{\sqrt{x}}{2} \quad \text{(load curve)}$$

The above load curve also fulfills the another condition which is :

At $x = 12$, $y = \sqrt{3}$

$$\therefore \qquad \left(\sqrt{3}\right)^2 = \frac{12}{4} \qquad \therefore \quad 3 = 3$$

The average load of the factory on the diesel power plant is given by :

$$L_{av} = \frac{1}{8}\int_4^{12} y \, . \, dx = \frac{1}{8}\int_4^{12} \frac{\sqrt{x}}{2} \, dx$$

$$= \frac{1}{16}\left[\frac{2}{3}(x)^{1.5}\right]_4^{12} = \frac{1}{24} \; [(12)^{1.5} - (4)^{1.5}]$$

$$= 1.4 \text{ MW}$$

(*i*) Load factor and capacity factor :

$$\textit{Load factor} \qquad = \frac{L_{av}}{L_{\max}} = \frac{1.4}{\sqrt{3}} = \mathbf{0.808.} \quad \textbf{(Ans.)}$$

$$\textit{Capacity factor} \qquad = \frac{L_{\max}}{\text{Plant capacity}} = \frac{\sqrt{3}}{2}$$

$$= \mathbf{0.866.} \quad \textbf{(Ans.)}$$

(*ii*) Energy consumption per month :

Energy consumption per month,

$$E = (L_{av} \times 8) \times 26$$

$$= (1.4 \times 8 \times 1000) \times 26$$

$$= 291200 \text{ kWh}$$

(*iii*) Electrical charges to be paid by the factory :

Electrical charges to be paid by the factory

$$= L_{\max} \times 60 + E \times 2.75$$

$$= \sqrt{3} \times 60 + 291200 \times 2.75$$

$$= ₹\ \mathbf{800904.} \quad \textbf{(Ans.)}$$

Example 9.44. *The daily load curve for a power plant is given by the following equation :*

$$L = 350 + 10t - t^2$$

where t is time in hours from 0 to 24 hours and L is in MW calculate :

(*i*) *Value of maximum load and when it occurs, and*

(*ii*) *Load factor of the plant.*

Draw load curve and load duration curve. **(P.U.)**

Solution. Equation of the load curve,

$$L = 350 + 10t - t^2 \qquad \text{...(Given)}$$

(*i*) Value of maximum load and when it occurs :

The condition for finding the value of maximum load is $\frac{dL}{dt} = 0$

$$\therefore \qquad \frac{d}{dt}(350 + 10t - t^2) = 0 \quad \text{or} \quad 10 - 2t = 0$$

$$\therefore \qquad t = 5 \text{ hours.}$$

Thus, the *maximum load occurs at 5th hour during the day.* **(Ans.)**

$$\therefore \qquad L_{max} = 350 + 10 \times 5 - 5^2 = \mathbf{375\ MW.} \quad \textbf{(Ans.)}$$

(*ii*) Load factor of the plant :

The average load on the plant is given by

$$L_{av} = \frac{1}{24}\int_0^{24} L \, . \, dt = \frac{1}{24}\int_0^{24} (350 + 10t - t^2)\, dt$$

$$= \frac{1}{24}\left[350t + 10 \times \frac{t^2}{2} - \frac{t^3}{3}\right]_0^{24}$$

$$= \frac{1}{24}\left[350 \times 24 + 10 \times \frac{(24)^2}{2} - \frac{(24)^3}{3}\right]$$

$$= 278 \text{ MW}$$

$$\therefore \qquad \text{Load factor} = \frac{L_{av}}{L_{max}} = \frac{278}{375} = \mathbf{0.7413.} \quad \textbf{(Ans.)}$$

Load curve and load duration curve :

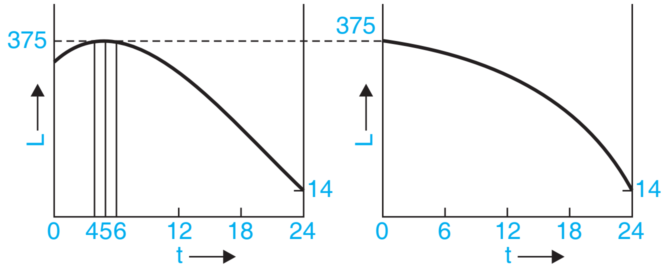
- The *'load curve is' the representation of load with respect to time.*
- The *'load duration curve' is the representation of load with respect to time in descending order.*

In order to draw these curves, we need to calculate the values of L when $t = 0, 1, 2, 3, ... \; 24$ hours and these values are tabulated below :

(Eqn. of the load curve $L = 350 + 10t - t^2$), At $t \simeq 0$, $L = 350$ MW

t (h)	L (MW)	t (h)	L (MW)
1	359	13	311
2	366	14	294
3	371	15	275
4	374	16	254
5	375	17	231
6	374	18	206
7	371	19	179
8	366	20	150
9	359	21	119
10	350	22	86
11	339	23	51
12	326	24	14

From the above data the load curve and load duration curve are drawn as shown in Fig. 9.19 (*a*) and (*b*) respectively.



(a) Load curve. (b) Load duration curve.

Fig. 9.19

HIGHLIGHTS

1. Types of loads : (*i*) Residential load, (*ii*) Commercial load, (*iii*) Industrial load, (*iv*) Municipal load, (*v*) Irrigation load, and (*vi*) Traction load.

2. A *load curve* is a graphic record showing the power demands for every instant during a certain time interval. The area under the load curve represents the energy generated in the period considered.

3. The cost of a power system includes the following :

A. *Capital cost or fixed cost :*

(*i*) Initial cost (*ii*) Interest
(*iii*) Depreciation cost (*iv*) Taxes
(*v*) Insurance

B. *Operational cost :*

(*i*) Fuel cost (*ii*) Operating labour cost
(*iii*) Maintenance cost (*iv*) Supplies
(*v*) Supervision (*vi*) Operating taxes.

4. The following methods are used to calculate the depreciation cost :

(*i*) Straight line method. (*ii*) Percentage method.
(*iii*) Sinking fund method. (*iv*) Unit method.

5. The economics of power plant is greatly influenced by :

(*i*) Load factor (*ii*) Demand factor
(*iii*) Utilisation factor.

6. The performance of a plant can be precisely represented by the *input-output* curve from the tests conducted on individual power plant. In general input-output may be represented as follows :

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

where I = input (in millions of kcal/h or kJ/h in case of thermal plants and m^3/s of water in case of hydro-plants)
L = output (in MW or kW)
a, b, c, d = constants.

7. 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

$$\frac{dI_1}{dL_1} = \frac{dI_2}{dL_2} = \frac{dI_3}{dL_3} = \ldots\ldots \frac{dI_n}{dL_n} .$$

8. The general tariff form is given by :

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

where, z = Total amount of bill for the period considered.
x = Maximum demand in kW.
y = Energy consumed in kWh during the period considered.
a = Rate per kW of maximum demand.
b = Energy rate per kWh.
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.

9. Various types of *tariff* are :

(*i*) Flat demand rate
(*ii*) Straight meter rate
(*iii*) Block meter rate
(*iv*) Hopkinson demand rate (Two-part tariff)
(*v*) Doherty rate (Three-part tariff)
(*vi*) Wright demand rate.

THEORETICAL QUESTIONS

1. Define the following terms :
   (*i*) Connected load (*ii*) Demand
   (*iii*) Demand factor (*iv*) Load factor
   (*v*) Diversity factor (*vi*) Utilisation factor.

2. Explain briefly the following :
   (*i*) Load curve (*ii*) Load duration curve.

3. What is the significance of load curves ?

4. Enumerate various types of loads.

5. List the factors which should be considered while designing a power plant.

6. What are the considerations on which the location of a power plant depends ?

7. List the points which should be taken care of while deciding about power plant building and its layout.

8. List the various costs which go to form the total cost of a power system.

9. Explain briefly the following :
   (*i*) Capital or fixed cost (*ii*) Operational cost.

10. What do you mean by depreciation ?

11. Enumerate and explain briefly various methods used to calculate the depreciation cost.

12. Name the elements that make up the operating expenditure of a power plant.

13. What points should be considered while choosing the type of generation ?

14. Discuss the economic loading of combined steam and hydro-plants.

15. How can the power generation cost be reduced ?

16. What do you understand by the term tariff ?

17. What are the objectives and requirements of tariff ?

18. Enumerate various types of tariff and explain any two of them.

19. Explain briefly the following tariff :
   (*i*) Straight meter rate (*ii*) Block meter rate
   (*iii*) Doherty rate (three-part tariff).

UNSOLVED EXAMPLES

1. The maximum demand of a power station is 80000 kW and the load curve is defined as follows :

Time (hours) :	0–6	6–8	8–12	12–14	14–18	18–22	22–24
Load (MW) :	40	50	60	50	70	80	40

   (*i*) Determine the load factor of power station.
   (*ii*) What is the load factor of standby equipment rated at 25 MW that takes up all load in excess of 60 MW ? Also calculate its use factor.

[**Ans.** (*i*) 0.71, (*ii*) 0.75, 0.6]

2. The following load is to be supplied by a power station :

Load (MW) :	30	90	60	100	50
Time (hours) :	0–6	6–12	12–14	14–18	18–24

   (*i*) Draw the load curve.
   (*ii*) Draw the load duration curve.
   (*iii*) Choose suitable generating units to supply the load.
   (*iv*) Calculate the load factor.
   (*v*) Calculate plant capacity factor.

[**Ans.** (*iii*) 30 MW (4 units including standby unit), 10 MW (one unit), (*iv*) 0.64, (*v*) 0.49]

3. The yearly duration curve of a certain plant can be considered as a straight line from 150 MW to 40 MW. Power is supplied with one generating unit of 100 MW capacity and two units of 50 MW capacity each. Determine :
   (*i*) Installed capacity (*ii*) Load factor
   (*iii*) Plant factor (*iv*) Maximum demand
   (*v*) Utilization factor.

[**Ans.** (*i*) 200 MW, (*ii*) 0.633, (*iii*) 0.475, (*iv*) 150 MW, (*v*) 0.75]

4. A generating station has a maximum demand of 20 MW, a load factor of 0.6, a plant capacity of 0.48 and a plant use factor of 0.80. Find :
   (*i*) The daily energy produced.
   (*ii*) The reserve capacity of the plant.
   (*iii*) The maximum energy that could be produced if the plant were running all the time.
   (*iv*) The maximum energy that could be produced daily, if the plant when running, according to operating schedule, were fully loaded.

[**Ans.** (*i*) 2.88 × 10^5 kWh, (*ii*) 5000 kW, (*iii*) 2.88 × 10^5 kWh, (*iv*) 3.60 × 10^5 kWh]

5. A proposed power station has to supply load as follows :

Time (hours) :	01–08	08–12	12–17	17–20	20–23	23–01
Load (MW) :	10	20	25	18	35	20

After drawing the load curve, find out the load factor. Also choose suitable generating units to supply this load, maintaining reliability of supply. Prepare operation schedule for the machine and calculate plant use factor.

[**Ans.** 0.56, 0.92]

6. A generating station supplies the following loads : 15 MW ; 12 MW ; 8 MW and 0.5 MW. The station has a maximum demand of 20 MW and the annual load factor is 0.5. Find :
   (*i*) Number of units supplied annually.
   (*ii*) Diversity factor.

[**Ans.** (*i*) 876 × 10^5 kWh, (*ii*) 1.775]

7. A base load power station and standby power station share a common load as follows :

Base load station annual output = 150 × 10^6 kWh ; Base load station capacity = 35 MW ; Maximum demand on base load station = 30 MW ; Standby station capacity = 18 MW ; Standby station annual output = 140 × 10^6 kWh ; Maximum demand (peak load) on standby station = 15 MW. Determine the following for both power stations :

(*i*) Load factor
(*ii*) Capacity factor (plant factor).

[**Ans.** Base load station : (*i*) 0.57 (*ii*) 0.49
Standby power station : (*i*) 0.107 (*ii*) 0.09]

8. A power system has the following load particulars :

	Maximum demand	Load factor	Diversity between consumers
1. Residential load :	1000 kW	0.2	1.3
2. Commercial load :	2000 kW	0.3	1.1
3. Industrial load :	5000 kW	0.8	1.2

Overall diversity factor may be taken as 1.4.

Determine the following :

(*i*) Maximum demand on system.
(*ii*) Daily energy consumption (total).
(*iii*) Overall load factor.
(*iv*) Connected load (total) assuming that demand factor for each load is unity.

9. The following data is available for a steam power station : Maximum demand = 25000 kW ; Load factor = 0.4 ; Coal consumption = 0.86 kg/kWh ; Boiler efficiency = 85% ; Turbine efficiency = 90% ; Price of coal = ₹ 55 per tonne.

Determine the following :

(*i*) Thermal efficiency of the station.
(*ii*) Coal bill of the plant for one year.

[**Ans.** (*i*) 76.5%, (*ii*) ₹ 4143480]

10. The daily load curve of a power plant is given by the table below :

Time :	12	2	4	6	8	10	12	2	4	6	8	10	12
Load (MW) :	2	2.5	3	4	6	6.5	6.5	5	6	8	9	5	2

(*i*) Find the daily load factor.
(*ii*) All loads in excess of 400 kW are carried out by unit No. 2 rated at 600 kW. Find its use factor.

[**Ans.** (*i*) 0.814, (*ii*) 0.417]

11. The annual peak load on a 30 MW power station is 25 MW. The power station supplies load having maximum demands of 10 MW, 8.5 MW, 5 MW and 4.5 MW. The annual load factor is 0.45. Find :

(*i*) Average load (*ii*) Energy supplied per year
(*iii* Diversity factor (*iv*) Demand factor.

[**Ans.** (*i*) 11.25 MW, (*ii*) 98.55 × 10^6 kWh, (*iii*) 1.12, (*iv*) 0.9]

12. A generating station supplies the following loads : 15 MW, 12 MW, 8.5 MW, 6 MW and 0.45 MW. The station has a maximum demand of 22 MW. The annual load factor of the station is 0.48. Calculate :

(*i*) The number of units supplied annually,
(*ii*) The diversity factor. (*iii*) The demand factor.

[**Ans.** (*i*) 92.5 × 10^6 kWh, (*ii*) 1.907, (*iii*) 0.525]

13. A power station has a maximum demand of 15 MW, a load factor of 0.7, a plant capacity factor of 0.525 and a plant use factor of 0.85. Find :

(*i*) The daily energy produced.
(*ii*) The reserve capacity of the plant.
(*iii*) The maximum energy that could be produced daily if the plant operating schedule is fully loaded when in operation.

[**Ans.** (*i*) 252000 kWh, (*ii*) 5000 kW, (*iii*) 296470 kWh]

14. Determine the annual cost of a feed water softner from the following data :

Cost = ₹ 80000 ; Salvage value = 5% ; Life = 10 years ; Annual repair and maintenance cost = ₹ 2500 ; Annual cost of chemicals = ₹ 5000 ; Labour cost per month = ₹ 300 ; Interest on sinking fund = 5%. [**Ans.** ₹ 17,140]

15. Estimate the generating cost per kWh delivered from a generating station from the following data :

Plant capacity = 50 MW
Annual load factor = 0.4
Capital cost = ₹ 1.2 crores
Annual cost of wages, taxation etc. = ₹ 4 lacs
Cost of fuel, lubrication, maintenance etc. = 1.0 paise per kWh generated.

Interest 5% per annum, depreciation 5% per annum of initial value. [**Ans.** 1.91 paise/kWh delivered]

16. A 100 MW, steam power station is estimated to cost ₹ 20 crores. The operating expenses are estimated as follows :

Cost of fuel and oil = ₹ 140 lacs per annum
Transportation and storage = ₹ 20 lacs per annum
Salaries and wages = ₹ 20 lacs per annum
Miscellaneous = ₹ 20 lacs per annum

Reckoning interest and depreciation at 10% of the capital cost, calculate the cost of generation per unit, if the average load factor of the power station is 0.6.

What economics could be affected if the load factor was improved to 0.8, the operating expenses increasing by only 10% thereby.

[**Ans.** 6 p/kWh, 21% reduction in cost of generation]

17. A steam station has two 110 MW units. Following cost data are given :

Particulars	**Unit A**	**Unit B**
Capital cost	₹ 2000 per kW	₹ 2500 per kW
Fixed charge rate	10 per cent	10 per cent
Capacity factor	0.55	0.6
Fuel consumption	1 kg/kWh	0.9 kg/kWh
Fuel cost	₹ 80 per 1000 kg	₹ 80 per 1000 kg
Annual cost of operating, labour maintenance and supplies	20 per cent of annual cost	15 per cent of annual cost
Utilisation factor	1	1

Calculate the following :

(*i*) Annual plant cost and generation cost of unit A.
(*ii*) Annual plant cost and generation cost of unit B.

(*iii*) Overall generation cost of the station.

[**Ans.** (*i*) ₹ 7,28,78,080 ; 13.75 p/kWh, (*ii*) ₹ 75.371648 × 10^6 ; 13.036 p/kWh, (*iii*) 13.378 p/kWh]

18. The annual costs of operating a 15,000 kW thermal power station are as follows :

Cost of plant = ₹ 900 per kW

Interest, insurance, taxes on plant = 5 per cent

Depreciation = 5 per cent

Cost of primary distribution system = ₹ 500000

Interest, insurance, taxes and depreciation on primary distribution system = 5 per cent

Cost of secondary distribution system = ₹ 900000

Interest, taxes, insurance and depreciation on secondary distribution system = 5 per cent

Maintenance of secondary distribution system = ₹ 180000

Plant maintenance cost

(*i*) Fixed cost = ₹ 30000

(*ii*) Variable cost = ₹ 40000

Operating costs = ₹ 600000

Cost of coal = ₹ 60 per tonne

Consumption of coal = 30000 tonnes

Dividend to stock-holders = ₹ 1000000

Energy loss in transmission = 10 per cent

Maximum demand = 14000 kW

Diversity factor = 1.5

Load factor = 0.7

Determine : (*i*) Charge per kW per year, (*ii*) Rate per kWh.

[**Ans.** (*i*) ₹ 116.6, (*ii*) 3.4 p/kWh]

19. It is proposed to supply a load with a maximum demand of 100 MW and a load factor of 0.4. Choice is to be made from steam, hydro and nuclear power plants. Calculate the overall cost per kWh in case of each machine :

Cost	Steam power plant	Hydro power plant	Nuclear power plant
Capital cost per kW installed	₹ 1800	₹ 3600	₹ 5000
Interest	12%	10%	10%
Depreciation	12%	8%	10%
Operating cost per kWh	15 paise	5 paise	10 paise
Transmission and distribution cost/kWh	0.2 paise	0.8 paise	0.2 paise

[**Ans.** 27.52 p ; 23.57 p ; 38.73 p]

20. A power plant of 150 MW installed capacity has the following data :

Capital cost = ₹ 1800/kW installed ; Interest and depreciation = 12 per cent ;

Annual load factor = 0.6 ; Annual capacity factor = 0.5 ; Annual running charges = ₹ 30 × 10^6 ; Energy consumed by the power plant auxiliaries = 6 per cent. Calculate :

(*i*) Reserve capacity (*ii*) Generating cost.

[**Ans.** (*i*) 25 MW, (*ii*) 10.10 paise]

21. Compare the annual cost of supplying a factory load having a maximum demand of 1 MW at a load factor of 50% by energy obtained from

(*a*) Nuclear power plant (*b*) Public supply

Nuclear power plant

Capital cost = ₹ 50,000

Cost of fuel = ₹ 600 per 1000 kg

Fuel consumption = 30 g per kWh generated

Cost of maintenance etc. = ₹ 0.005 per kWh generated

Wages = ₹ 20000 per annum

Interest and depreciation = 10 per cent.

Public supply : ₹ 50 per kW + ₹ 0.03 per kWh generated.

[**Ans.** ₹ 170740 ; ₹ 181400]

22. A system with a maximum demand of 1,00,000 kW and a load factor of 30% is to be supplied by either (*a*) steam station alone or (*b*) a steam station in conjunction with a water storage scheme, the latter supplying 100 million units with a maximum output of 40000 kW. The capital cost of steam and storage stations are ₹ 600 per kW and ₹ 1,200 per kW respectively. The corresponding operating costs are 15 paise and 3 paise per kWh respectively. The interest on capital cost is 15% per annum. Calculate the overall generating cost per kWh and state which of the two projects will be economical.

[**Ans.** 18.425 p/kWh, 15.23 p/kWh]

23. A power station has the installed capacity of 120 MW. Calculate the cost of generation, other data pertaining to power station are given below :

Capital cost = ₹ 200 × 10^6

Rate of interest and depreciation = 18 per cent

Annual cost of fuel oil, salaries and taxation = ₹ 24 × 10^6

Load factor = 0.4

Also calculate the saving in cost per kWh if the annual load factor is raised to 0.5.

[**Ans.** 14.25 paise ; 2.84 paise]

24. A 50 MW generating station has the following data :

Capital cost = ₹ 15 × 10^6 ; Annual taxation = ₹ 0.4 × 10^6 ; Annual salaries and wages = ₹ 1.2 ×10^6 ; Cost of coal = ₹ 65 per tonne ; Calorific value of coal = 5500 kcal/kg ; Rate of interest and depreciation = 12 per cent ; plant heat rate = 33000 kcal/kWh at 100% capacity factor. Calculate the generating cost/kWh at 100% capacity factor.

[**Ans.** 39.77 p/kWh]

25. An input output curve of a 10 MW thermal station is given by an equation

$$I = 10^6(18 + 12L + 0.5L^2) \text{ kcal/hour}$$

where I is in kcal/hour and L is the load on power plant in MW.

Find : (*i*) The load at which the efficiency of the plant will be maximum.

(*ii*) The increase in output required to increase the station output from 5 MW to 7 MW by using the input-output equation and by incremental rate curve.

[**Ans.** (*i*) 6 MW, (*ii*) 36 × 10^6 kcal/hour]

26. The input-output curve of a 60 MW power station is given by :

$$I = 10^6(8 + 8L + 0.4L^2) \text{ kcal/hour}$$

where I is the input in kcal/hour and L is load in MW.

(*i*) 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.

(*ii*) 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.

[**Ans.** (*i*) 38592 × 10^6 kcal/day, (*ii*) 4000 kcal/kWh]

27. The incremental fuel costs for two generating units 1 and 2 of a power plant are given by the following equations :

$$\frac{dF_1}{dP_1} = 0.06P_1 + 11.4$$

$$\frac{dF_2}{dP_2} = 0.07P_2 + 10$$

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

(*i*) Find the economic loading of the two units when the total load to be supplied by the power station is 150 MW.

(*ii*) Find the loss in fuel costs per hour if the load is equally shared by the two units.

[**Ans.** (*i*) P_1 = 70 MW, P_2 = 80 MW, (*ii*) ₹ 1.63 per hour]

28. The incremental fuel costs for two generating units 1 and 2 of a power plant are given by the following equations :

$$\frac{dF_1}{dP_1} = 0.065P_1 + 25$$

$$\frac{dF_2}{dP_2} = 0.08P_2 + 20$$

where F is fuel cost in rupees per hour and P is power output in MW. Find :

(*i*) the economic loading of the two units when the total load supplied by the power plants is 160 MW.

(*ii*) the loss in fuel cost per hour if the load is equally shared by both units.

[**Ans.** (*i*) P_1 = 53.5 MW, P_2 = 106.5 MW, (*ii*) ₹ 35/hour]

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

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

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

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

Find the most economical loading when the load taken by both units is 30 MW. [**Ans.** L_1 = 20 MW, L_2 = 10 MW]

30. Two electrical units used for the same purpose are compared for their economical working :

(*i*) Cost of Unit-1 is ₹ 5000 and it takes 100 kW.

(*ii*) Cost of Unit-2 is ₹ 14000 and it takes 60 kW.

Each of them has a useful life of 40000 hours. Which unit will prove economical if the energy is charged at ₹ 80 per kW of maximum demand per year and 5 p. per kWh ?

Assume both units run at full load.

[**Ans.** Unit-1 : ₹ 6.039 ; Unit-2 : ₹ 3.898, Unit-2 is more economical]

31. A new industry requires maximum demand of 800 kW at 30% load factor. The following two power supplies are available :

(*i*) *Public supply* charges ₹ 50/kW of maximum demand and 4 p. per kWh.

Capital cost = ₹ 80000

Interest and depreciation = 10 per cent.

(*ii*) *Private oil engine generating station*.

Capital cost = ₹ 30000

Interest and depreciation = 12 per cent

Maintenance and labour charges = 1 p. per kWh energy generated

Fuel consumption = 0.35 kg/kWh

Cost of fuel = 8 paise/kg.

Find which supply will be more economical ?

[**Ans.** (*i*) 6.3 p/kWh, (*ii*) 5.1 p/kWh ; oil engine generation is more preferable]

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

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

(*ii*) A steam station in conjunction with pump-storage plant which is capable of supplying 120 × 10^6 kWh 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 = ₹ 1800/kW of installed capacity ; Capital cost of pump storage plant = ₹ 1200/kW of installed capacity ; Operating cost of steam plant = 0.5 p/kWh ; Operating cost of pump storage plant = 0.4 p./kWh.

Interest and depreciation together on capital invested should be taken as 12 per cent.

Assume that no spare capacity is required.

[**Ans.** (*i*) 11.16 p./kWh, (*ii*) 8.42 p./kWh]

33. The monthly electricity consumption of a residence can be approximated as under :

Light load : 4 tube lights 40 watts each working for 3 hours daily ; *Fan load* : 4 fans 100 watts each working for 5 hours daily ; *Refrigerator load* : 1 kWh daily ; *Miscellaneous load* : 1 kW for one hour daily.

Find the monthly bill at the following tariff :

First 15 units : ₹ 0.50/kWh, Next 25 units : ₹ 0.40 per kWh ; Remaining units : ₹ 0.30 per kWh ; Constant charge : ₹ 2.50 per month. Discount for prompt payment = 5% .

[**Ans.** ₹ 45.20]

34. An industrial undertaking has a connected load of 110 kW. The maximum demand is 90 kW. On an average each machine works for 60 per cent time. Find the yearly expenditure on electricity if the tariff is :

₹ 1000 + ₹ 100 per kW of maximum demand per year + ₹ 0.10 per kWh. [**Ans.** ₹ 67186]

35. A Hopkinson demand rate is quoted as follows :

Demand rates

First 1 kW of maximum demand = ₹ 5/kW/month
Next 4 kW of maximum demand = ₹ 4/kW/month
Excess over 5 kW of maximum demand = ₹ 3/kW/month

Energy rates

First 50 kWh = 6 paise/kWh
Next 50 kWh = 4 paise/kWh
Next 200 kWh = 3 paise/kWh
Next 400 kWh = 2.5 paise/kWh
Excess over 700 kWh = 2 paise/kWh

Determine : (*i*) The monthly bill for a total consumption of 1500 kWh and a maximum demand of 12 kW. Also find the unit energy cost.

(*ii*) Lowest possible bill for a month and corresponding unit energy cost.

[**Ans.** (*i*) ₹ 79, 5.26 paise/kWh, (*ii*) ₹ 46.33, 3.09 paise/kWh]

36. Find the cost of generation per kWh from the following data :

Capacity of the plant = 120 MW
Capital cost = ₹ 1200 per kW installed
Interest and depreciation = 10 per cent on capital
Fuel consumption = 1.2 kg/kWh
Fuel cost = ₹ 40 per tonne
Salaries, wages, repairs and maintenance = ₹ 600000 per year
The maximum demand = 80 MW
Load factor = 40%.

[**Ans.** 10.18 paise/kWh]

37. The following data relate to a 2200 kW diesel power station :

The peak load on the plant = 1600 kW
Load factor = 45%
Capital cost per kW installed = ₹ 1000
Annual costs = 15 per cent of capital
Annual operating costs = ₹ 60000
Annual maintenance cost :
(*i*) Fixed = ₹ 10000
(*ii*) Variable = ₹ 20000
Cost of fuel = ₹ 0.4 per kg
Cost of lubricating oil = ₹ 1.25 per kg
C.V. of fuel = 10000 kcal/kg
Consumption of fuel = 0.5 kg/kWh
Consumption of lubricating oil = 0.0025 kg/kWh

Determine the following :

(*i*) The annual energy generated.
(*ii*) The cost of generation (per kWh).

[**Ans.** (*i*) 6.3 × 10^6 kWh/year, (*ii*) 27 paise/kWh]

38. The following data relate to a steam power station of 120 MW capacity which takes 100 MW peak demand at 80% load factor :

Annual cost towards interest and depreciation = ₹ 100/kW installed ; Operating costs = ₹ 1200 × 10^3/year ; Maintenance costs = ₹ 200 × 10^3/year (fixed) and = ₹ 400 × 10^3/year (variable) ; Miscellaneous costs = ₹ 100 × 10^3/year ; Cost of coal used = ₹ 32/ton ; C.V. of fuel used = 6400 kcal/kg ; Overall efficiency of the plant = 20 per cent ; Steam consumption in kg/kWh = (0.8 + 3.5 × load factor).

Determine the following :

(*i*) Coal cost per year.
(*ii*) Overall cost of generation (paise/kWh).

[**Ans.** (*i*) ₹ 15 × 10^6/year, (*ii*) 4.12 paise/kWh]

39. A power system requires a maximum load of 80 MW at 35% load factor. It can be supplied by any of the following schemes :

(*i*) A steam plant capable to supply whole load.
(*ii*) 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.

Plant	Capital cost	Operating cost	Transmission cost
Steam plant	₹ 600/kW installed	4.8 paise/kWh	Negligible
Hydro plant	₹ 1400/kW installed	1.2 paise/kWh	0.3 paise/kWh

Assume interest and depreciation at 12 per cent of capital for steam plant and 10 per cent of capital for hydro plant. Calculate the overall cost per kWh.

(*iii*) If the whole load is supplied by a nuclear plant, determine annual cost. Take capital cost of ₹ 2500/kW and running cost of 2.5 paise/kWh. Assume interest and depreciation as 10 per cent per annum.

[**Ans.** (*i*) 7.05 paise/kWh, (*ii*) 5.98 paise/kWh, (*iii*) 10.67 paise/kWh]

40. The following data relate to a power plant of 120 MW capacity :

Capital cost = ₹ 1500/kW ; Interest and depreciation = 10 per cent on capital ; Annual running charges = ₹ 20 × 10^6 ; Profit to be gained = 10 per cent of the capital ; The energy consumed by the power plant auxiliaries = 5 per cent of generated ; The annual load factor = 0.6 ; Annual capacity factor = 0.5.

Calculate the following :

(*i*) The reserve capacity.
(*ii*) The cost of generation per kWh.

[**Ans.** (*i*) 20 MW, (*ii*) 9.3 paise/kWh]

41. A small generating unit of 5,000 kW capacity supplies the following loads :

(*i*) Street-light load with maximum demand of 200 kW at 0.3 load factor.
(*ii*) Small industrial load with maximum demand of 1800 kW at a load factor of 0.5.

(*iii*) Domestic consumers with a maximum demand of 3000 kW at a load factor of 0.2.

Find the overall energy rate for each type of consumer using the following data :

Capital cost of the plant = ₹ 1,800/kW of installed capacity

Total running cost = ₹ 6,20,000 per year

Annual rate of depreciation and interest on capital cost is 10%.

[**Ans.** (*i*) 11.4 paise/kWh, (*ii*) 8.65 paise/kWh, (*iii*) 14.8 p/kWh]

42. The following data relate to a 15 MW thermal plant :

Capital cost of plant = ₹ 1200/kW ; Interest, insurance and depreciation = 10% of the plant ; Capital cost of primary and secondary distribution = ₹ 15 × 10^5 ; Interest, insurance and depreciation on the capital cost of primary and secondary distribution = 5% of capital cost ; Plant maintenance cost = ₹ 80 × 10^3 per year ; Maintenance cost of primary and secondary equipments = ₹ 2 × 10^5 per year ; Salaries and wages = ₹ 6 × 10^5 per year ; Consumption of coal = 40 × 10^3 tonnes per year ; Cost of coal = ₹ 80 per tonne ; Dividend to stockholders = ₹ 12 × 10^5 per year ; Energy loss in transmission = 10% ; Diversity factor = 1.6 ; Load factor = 0.8 ; Maximum demand = 14 MW.

Devise a two-part tariff and find the average cost per kWh.

[**Ans.** Fixed charge per kW = 146, charge for energy consumption = 4.63 paise/kWh ; Average cost of supply = 8.1 paise/kWh]

43. The following data relate to a 12 MW capacity thermal plant :

Peak load = 10 MW
Annual load factor = 70%
Cost of the plant = ₹ 700/kW installed capacity
Interest, insurance and depreciation = 10 per cent of the capital cost
Cost of transmission and distribution system = ₹ 300 × 10^3
Interest, depreciation on distribution system = 5 per cent
Operating cost = ₹ 300 × 10^3 per year
Cost of coal = ₹ 50/ton
Plant maintenance cost = ₹ 25,000 per year (fixed)
= ₹ 35,000 per year (running)
Coal used = 30,000 tons/year.

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

(*i*) Design a two-part tariff.

(*ii*) Determine overall cost of generation in paise/kWh.

[**Ans.** (*i*) ₹ 88/kW + 3 paise/kWh, (*ii*) 4.43 paise/kWh]

44. 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 as given below :

Diesel : ₹ (30/kW + 0.05/kWh)

Steam : ₹ (120/kW + 0.0125/kWh). [**Ans.** 0.275]

45. A 30 H.P. motor connected to a condensate pump has been burnt beyond economical repairs. Two alternatives have been proposed to replace it by :

	Cost	**η at full load**	**η at half load**
Motor A	₹ 6000	90%	86%
Motor B	₹ 4000	85%	82%

The life of each motor is 20 years and its salvage value is 10 per cent of the initial value. The rate of interest is 5 per cent annually. The motor operates at full load for 25 per cent of the time and at half load for the remaining period. The annual maintenance cost of motor *A* is ₹ 420 and that of motor *B* is ₹ 240. The energy rate is 10 paise/kWh.

Which motor will be economical ?

[**Ans.** Motor A ; Total cost : Motor A = ₹ 14,777/year Motor B = ₹ 15135/year]

46. The following proposals are under consideration for an industry which has a maximum demand of 50 MW and a load factor of 0.4.

(*i*) A steam plant having an initial cost of ₹ 1000/kW and maintenance cost is 2 paise/kWh. The coal of C.V. of 6150 kcal/kg is used. The overall efficiency of the plant is 25 per cent.

(*ii*) A hydro-plant having a capital cost of ₹ 3000/kW and running cost of 0.5 paise/kWh.

Assuming interest and depreciation rate of 12 per cent for steam plant and 9 per cent for hydro-plant, determine the price of coal above which steam station is uneconomical. [**Ans.** ₹ 49.7/ton]

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

High voltage : ₹ 45/kW per year + paise 3.5/kWh

Low voltage : ₹ 47/kW per year + paise 4/kWh

In order to have high voltage supply, consumer has to install his own transformer which costs ₹ 100/kW. The losses in the transformer are 3 per cent 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 per cent of capital and working weeks per year 50. Assume the load of the consumer as 1 MW. [**Ans.** 49 hours per week]

48. The expected annual cost of power system supplying the energy to 40,000 consumers is tabulated below :

Fixed charges = ₹ 2400 × 10^3
Energy charges = ₹ 1716 × 10^3
Consumer charges = ₹ 210 × 10^3
Profit = ₹ 168 × 10^3
Maximum demand = 5000 kW
Diversity factor = 4
Energy supplied = 17 × 10^6 kWh.

Devise a three-part tariff allowing 25% of the profit in fixed charges, 50% in energy charges and remaining 25% in customer charges.

[**Ans.** ₹ 122/kW per year + 11 paise/kWh + ₹ 6.3 per consumer per year]

COMPETITIVE EXAMINATIONS QUESTIONS

1. (*a*) Define 'connected load', 'maximum demand', 'demand factor' and 'load factor'. Explain the importance of each in total power system.

(*b*) What are the different methods of regulating voltage in a power supply system ?

2. (*a*) Define 'diversity factor' and state the advantages of diversity of load in a power system.

(*b*) What are the different methods used to meet the variable loads ? Explain in details.

3. Find the cost of generation per kWh from the following data :

Capacity of the plant = 120 MW
Capital cost = ₹ 1,200 per kW installed
Interest and depreciation = 10% on capital
Fuel consumption = 1.2 kg/kWh
Fuel cost = ₹ 40 per tonne
Salaries, wages, repair and maintenance
= ₹ 6,00,000 per year

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

4. (*a*) State the advantages of combined working of different types of power plants.

(*b*) State the function of control board equipment.

(*c*) Describe earthing of a power system.

5. A power plant has the following annual load factors :

Load factor = 70%
Capacity factor = 50%
Use factor = 60%
Maximum demand = 20 MW

Find out :

(*a*) Annual energy production ;
(*b*) Reserve capacity over and above peak load ;
(*c*) Hours during which the plant is not in service per year.

6. The motor of a 30 H.P. condensate pump has been burnt beyond economical repairs. Two alternatives have been proposed to replace it by :

Motor A Cost = ₹ 6,000
η at full load = 90%
η at half load = 86%
Motor B Cost = ₹ 4,000
η at full load = 85%
η at half 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 ₹ 420 and that of motor *B* is ₹ 240. The energy rate is 10 paise per kWh.

Which motor would you recommend ?

7. (*a*) Discuss in detail how the load between two alternators can be divided for best economy. Explain the effect of load factor of a plant on the cost/kWh generated.

(*b*) What are the functions of switch gears ? Discuss the advantages of outdoor installations over indoor switch gear installations.

8. A new industry requires a maximum demand of 800 kW at 30% load factor. The following two supplies are available :

(*a*) Public supply charges ₹ 50/kW of maximum demand and 4 paise/kWh. The capital cost is ₹ 80,000 and interest and depreciation charges are 10%.

(*b*) A private oil engine station requires a capital of ₹ 3,00,000. The interest and depreciation on capital is 12%. The maintenance and labour charges are 1 p/kWh of energy generated. The fuel consumption is 0.35 kg/kWh and cost of fuel is 8 paise/kg.

Find out which supply is more economical.

9. (*a*) Explain the principle of economic distribution of load between generating stations.

(*b*) A small generating unit of 5,000 kW capacity supplies the following loads :

(*i*) Domestic consumers with a maximum demand of 3,000 kW at a load factor of 20 per cent ;

(*ii*) Small industrial load with a maximum demand of 2,000 kW at a load factor of 50 per cent.

Find the overall energy rate for both types of consumers.

Use the following data :

Capital cost of the plant
= ₹ 2,000 per kW of installed capacity

Total running cost
= ₹ 6,00,000 per year

Annual rate of depreciation and interest on capital cost is 10 per cent.

10. (*a*) What are the advantages of combined working of thermal power plant and hydro-electric plant ? Discuss briefly the need for coordination of these plants in power system.

(*b*) The maximum demand of a factor is 1000 kW at 30% load factor. The following two power supplies are available :

(*i*) **Public supply :** It charges ₹ 80/kW of maximum demand and 5 p/kWh. The capital cost is ₹ 1,00,000 and depreciation charges on the capital are 12%.

(*ii*) **Private oil engine station :** It requires ₹ 4,00,000 as capital and depreciation on capital is 10%. The maintenance and labour charges are 2 p/kWh energy generated. The fuel consumption is 0.3 kg/kWh and fuel cost is 20 p/kg.

Determine which supply is more economical.

11. (*a*) What is the effect of variable load on the power plant design and operation ?

(*b*) The loads on a power plant with respect to time for 24 hours are listed below :

Time (Hrs) :	0–6	6–10	10–12	12–16	16–20	20–24
Load (MW) :	30	50	60	70	80	40

Draw the load curve and find out the load factor of the power plant. If the load above 50 MW are taken by a stand-by unit of 30 MW capacity, find out the load factor of the stand by unit.

12. (*a*) Explain the principle of circuit interruption and its application in circuit brakers. Define the 'interruption capacity' and 'recovery voltage' of a circuit braker.

(*b*) What are the advantages of combined operation of power plants in a power system ? Explain with examples.

13. (*a*) Explain the effect of variable load on power plant operation and power plant design.

(*b*) The following data relate to a 10 MW thermal station :

Cost of plant = ₹ 3,000 per kW
Interest and taxes on cost of plant = 8% per annum
Depreciation of plant = 5% per annum
Cost of primary distribution = ₹ 800000
Interest, taxes, depreciation on cost of primary distribution system = 5%
Cost of coal with transportation = ₹ 100 per tonne
Operating cost = ₹ 800000 per annum
Plant maintenance cost (*i*) fixed = ₹ 40000 per annum
Plant maintenance cost (*ii*) variable = ₹ 50000 per annum
Installed capacity of plant = 10 MW
Maximum demand = 9 MW
Annual load factor = 70%
Consumption of coal per annum = 25000 tonnes.

Find : (*i*) the fixed cost of power generation per kW per annum ; (*ii*) the total cost of power generation per kWh. Cost of primary distribution is chargeable to generation.

14. (*a*) What is meant by powers plant economics ? What are the fixed and operating costs ?

(*b*) The following data relate to steam power station of 120 MW capacity which takes 100 MW peak demand at 80% load factor (L.F.).

Annual cost towards the interest and depreciation = ₹ 100/kW installed
Annual operating costs = ₹ 1200 × 10^3
Annual maintenance costs = ₹ 200 × 10^2 (fixed)
= ₹ 400 × 10^3 (variable)
Annual miscellaneous costs = ₹ 100 × 10^3
Cost of coal used = ₹ 32/tonne
Calorific value of fuel used = ₹ 6400 kcal/kg
Overall efficiency of the plant = 20%
Steam consumption in kg/kWh = (0.8 + 3.5 × L.F.)

Determine (*i*) costs per year, and (*ii*) overall cost of generation paise/kWh.

(*c*) Explain the different methods used for finding out the depreciation cost of the power plant.

15. (*a*) Discuss the methods of determining the depreciation of electrical power plant.

(*b*) 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 = ₹ 1000
Annual costs = ₹ 15% of capital
Annual operating costs = ₹ 60,000
Annual maintenance costs = Fixed ₹ 10,000
= Variable ₹ 20,000
Cost of fuel = ₹ 0.4 per kg
Cost of lubricating oil = ₹ 1.25 per kg
C.V. of fuel = 10,000 kcal/kg
Consumption of fuel = 0.5 kg/kWh
Consumption of lubricant oil = $\frac{1}{400}$ kg/kWh

Determine (*i*) the annual energy generated, and (*ii*) the cost of generation ₹/kWh.

16. (*a*) Explain with a neat sketch the water cooling system in diesel power plants using water softening plant and cooling tower.

(*b*) The annual costs of operating a 25 MW thermal plant are given below :

Capital cost of plant = ₹ 1200/kW
Interest + insurance + depreciation = 10% of plant cost
Capital cost of primary and secondary distribution = ₹ 15 × 10^5
Interest + insurance + depreciation on the capital cost of primary and secondary distribution = 5% of capital cost
Plant maintenance cost = ₹ 80 × 10^3 per year
Maintenance cost of primary and secondary equipment = ₹ 2 × 10^5 per year
Salaries and wages = ₹ 6 × 10^5 per year
Consumption of coal = 40 × 10^3 tonnes per year
Cost of coal = ₹ 80 per tonne
Dividend to stockholders = ₹ 12 × 10^5 per year
Energy loss in transmission = 10%
Diversity factor = 1.5
Load factor = 80%
Maximum demand = 14 MW.

Find the following :

(*i*) Total fixed cost ; (*ii*) Total variable charges ; (*iii*) Charges for energy consumption ; (*iv*) Average cost of supply.

17. (*a*) Explain load-duration curve. What are annual operating costs ? What are the factors that influence the depreciation of capital equipment ?

(*b*) The estimated total annual operating costs and capital charges for two power stations are given by the following expressions :

Annual cost for station *A* :

₹ (10^5 + 60 kW + 0.01 kWh)

Annual cost for station *B* :

₹ (6×10^4 + 35 kW + 0.02 kWh)

where kW represents the capacity of the station and kWh represents the total annual energy generated.

The stations are to be used to supply a common load having annual load duration curve approximated by a straight line, maximum and minimum loads being 50 MW and zero respectively.

Find the following :

(*i*) Which station should be used to supply the peak load ?
(*ii*) What should be its installed capacity ?
(*iii*) For how many hours per year should it be in operation to give the minimum total cost per unit generated ?

Calculate also the total cost per unit generated under these conditions.

18. (*a*) What are fixed costs and operating costs ?

(*b*) Name the major items of fixed costs and operating costs.

(*c*) A new housing development is to be added to the lines of a public utility system. There are 1000 apartments, each having a connected load of 4 kW ; also stores and services are included as given below :

Stores or Services	Connected load in kW	Demand factor in per cent
Laundry, Drug stores, etc.	50	60
1 Restaurant	60	52
2 Churches	20 each	56
3 Theatre	100	50

The demand factor of the apartments is 45 per cent. The group diversity factor of the residential load for this system is 3.5 and the peak diversity factor is 1.4. The commercial load group diversity factor is 1.5 and the peak diversity factor is 1.1.

Find the increase in peak demand on the total system delivery from the station bus resulting from addition of this development on the distribution system. Assume line losses as 5 per cent of delivery energy.

19. (*a*) Define 'diversity factor' and state the advantages of the diversity load on a power supply system.

(*b*) A load having a maximum demand of 100 MW and a load factor of 30% may be supplied by one the following schemes :

Scheme A : A steam thermal plant capable of supplying the whole load.

Scheme B : A steam thermal plant in conjunction with a pump storage plant capable of supplying 108 kWh of energy per year with a maximum load of 40 MW.

Find the cost of energy per unit in each case.

Use the following data :

Capital cost of the steam plant

= ₹ 3000/kW of installed capacity

Capital cost of the pump storage plant

= ₹ 2000/kW of installed capacity

Operating cost of steam plant

= 20 p/kWh

Operating cost of pump storage plant = 2 p/kWh

Interest and depreciation together on capital cost for both schemes = 15%

Assume reserve capacity of 20 MW for the steam plant in each scheme.

20. How do you define load factor, plant use factor and capacity factor ? What is the importance of diversity factor in the design of a steam power plant ?

21. (*a*) Explain the terms 'Maximum Demand' and 'Load Factor' with reference to a 'Power System'.

(*b*) A load having a maximum demand of 100 MW at 30% load factor may be supplied by one of the following schemes :

(*i*) A steam plant capable of supplying the whole load ;
(*ii*) A steam plant in conjunction with a pumped storage plant capable of supplying 10^6 kWh energy per year with a maximum load of 40 MW.

Using the following data, find the most economic scheme among the two

Capital cost of steam station is ₹ 1000/kW of installed capacity.

Capital cost of pumped storage plant is ₹ 700/kW of installed capacity. Operating cost of steam station = 2.5 NP/kWh. Interest and depreciation together on capital cost is 15%. Assume no reserve capacity is required for both the schemes.

Non-Conventional Power Generation and Direct Energy Conversion

10

10.1. INTRODUCTION TO ENERGY AND ENERGY SOURCES

10.1.1. Energy

Energy *is the capability to produce motion ; force ; work ; change in shape ; change in form etc.*

Energy exists in several forms such as :

—Chemical energy

—Nuclear energy

—Mechanical energy

—Electrical energy

—Internal energy

—Bio-energy in vegetables and animal bodies

—Thermal energy etc.

Energy may be *classified* as follows :

Energy :

1. *Stored in earth :*
   - (*i*) Chemically bonded :
     - (*a*) Oil
     - (*b*) Gas
     - (*c*) Coal
   - (*ii*) Geotherm
   - (*iii*) Atomic :
     - (*a*) Fission
     - (*b*) Fusion (futuristic)
2. *Continually received by earth :*
   - ● Solar insolation
     - (*a*) Ocean temp. difference
     - (*b*) Tidal
     - (*c*) Hydro
       - —Irrigation
       - —Other benefits (flood control etc.)
       - —Hydroelectric (no thermal limits)
     - (*d*) Wind
       - —Wind mill generator
     - (*e*) Direct
       - —*PVC*
       - —Concentrator—Steam turbine

Water input

↓

Thermocycle
—Steam turbo-generator
—Gas turbo-generator-combined cycle
—M.H.D combined cycle

Conservation
—Cogeneration
—High thermal generation
—low trans. loss
—High efficiency motors
—Curb wasteful use

- **Energy science** focusses attention on the *'energy'* and *'energy transformations'* involved in the various other branches of science, to National economy and civilization.
- **Energy technology** *is the applied part of energy sciences for work and processes, useful to human society, nations and individuals.*

— Energy technologies deal with plants and processes involved in the energy transformation and *analysis* of the *useful energy* ***(exergy)*** and *worthless energy* ***(anergy)***

— Energy technology co-relates various sciences and technologies

Characteristics of energy. Energy has the following *characteristics* :

(*i*) It can be stored.

(*ii*) It can neither be created nor destroyed.

(*iii*) It is available in several forms

(*iv*) It does not have absolute value.

(*v*) It is associated with a potential. Free flow of energy takes place only from a higher potential to a lower potential.

(*vi*) It can be transported from one system to other system or from one place to another.

(*vii*) The energy is measured in Nm or in joules.

(*viii*) The forms of energy are graded as per their availability or energy content.

- The total mass and energy in the closed system remains unchanged (as per law of conservation of energy).

Energy and thermodynamics :

"Thermodynamics" is a branch of energy which deals with conversion of heat into work or vice versa :

— More than 30 per cent energy conversion processes involve *thermodynamics*, while more than 30 per cent energy conversion processes involve *electromagnetic energy* and more than 30 per cent involve *chemical energy*.

In most of the energy conversion processes, First law and Second law of thermodynamics are applicable :

- *First law* of thermodynamics relates to *conservation of energy* and throws light on concept of internal energy.
- *Second law* of thermodynamics indicates the limit of *converting heat into work* and introduces the principle of increase of entropy. Following statements are based on this law :
  - — Spontaneous processes are irreversible.

- — The internal energy of the environment is worthless for obtaining useful work.
- — All forms of energy are not identical with reference to useful work.
- — Every energy conversion process has certain 'losses'.

Energy resources :

The various sources of energy can be *classified* as follows :

1. *Commercial primary energy resources :*
   - (*i*) Coal
   - (*ii*) Lignite
   - (*iii*) Oil and natural gas
   - (*iv*) Hydroelectric
   - (*v*) Nuclear fuels.
2. *Renewable energy sources :*
   - (*i*) Solar photo-voltaic
   - (*ii*) Wind
   - (*iii*) Hydrogen fuel-cell.
3. *New sources of energy :*

Most prominent *new sources of energy* as identified by UN are :

- (*i*) Tidal energy
- (*ii*) Ocean waves
- (*iii*) OTEC (Ocean Thermal Energy Conversion)
- (*iv*) Geothermal energy
- (*v*) Peat
- (*vi*) Tar sand
- (*vii*) Oil shales
- (*viii*) Coal tar
- (*ix*) Draught animals
- (*x*) Agricultural residues etc.

- — *Coal, oil, gas, uranium and hydro* are commonly known as ***commercial or conventional energy sources.*** These represent about 92% of the total energy used in the world.
- — *Firewood, animal dung and agricultural waste* etc. are called as ***non-commercial energy sources.***

These represent about 8% of the total energy used in the world.

- Renewable energy sources include both '*direct*' solar radiation intercepted by collectors (*e.g.* solar and flat-plate thermal cells) and '*indirect*' solar energy such as *wind*, *hydropower*, *ocean energy* and *biomass resources* that can be managed in a sustainable manner. *Geothermal* is considered renewable because the resource is unlimited.

Advantages of renewable energy sources :

1. These energy sources recur in nature and are inexhaustible.
2. The power plants using renewable sources of energy do not have any fuel cost and hence their running cost is negligible.
3. As renewables have low energy density, there is more or less no pollution or ecological balance problem.
4. These energy sources can help to save foreign exchange and generate local employment (since most of the devices and plants used with these sources of energy are simple in design and construction, having being made from local materials, local skills and by local people).
5. These are more site specific and are employed for local processing and application, their economic and technological losses of transmission and distribution being nil.
6. Since conversion technology tends to be flexible and modular, renewable energy can usually be rapidly deployed.

Limitations/Demerits :

1. Owing to the low energy density of renewable energy sources large size plants are required, and as such the cost of delivered energy is increased.
2. These energy sources are intermittent and also lack dependability.
3. The user of these sources of energy has to make huge additional investment before deriving any benefit from it (whereas in case of conventional energy sources, the processing cost has traditionally been borne by large industries which borrow money from a bank and then charge the customer for each unit of energy used).
4. These energy sources, due to their low energy density, have low operating temperatures leading to low efficiencies.
5. Since the renewable energy plants have low operational efficiency, the heat rejections are large which cause thermal pollution.
6. These energy sources are energy intensive.

Note. Energy cannot be economically stored in electrical form in large quantities. Energy in large quantities is stored in conventional forms (Hydro-reservoirs, coal stocks, fuel stocks, nuclear fuel stocks). Electrical energy is generated, transmitted and utilised almost simultaneously without intermediate storage in electrical form. Hence a large *electrical network* is formed *to pool up electrical energy* available from various generating stations and to distribute to various consumers over the large geographical area. Consumers draw power as per their load requirement (*e.g.* lighting, heating, mechanical drives etc.)

10.1.2. Non-Conventional Energy Sources

A plenty of energy is needed to sustain industrial growth and agricultural production. The existing sources of energy such as coal, oil, uranium etc. may not be adequate to meet the ever increasing energy demands. These conventional sources of energy are also depleting and may be exhausted at the end of the century or beginning of the next century. Consequently sincere and untiring efforts shall have to be made by the scientists and engineers in exploring the possibilities of harnessing energy from several non-conventional energy sources. The various non-conventional energy sources are as follows :

(*i*) Solar energy (*ii*) Wind energy
(*iii*) Energy from biomass and biogas
(*iv*) Ocean thermal energy conversion
(*v*) Tidal energy (*vi*) Geothermal energy
(*vii*) Hydrogen energy (*viii*) Fuel cells
(*ix*) Magneto-hydrodynamics generator
(*x*) Thermionic converter
(*xi*) Thermo-electric power.

Advantages of non-conventional energy sources :

The leading advantages of non-conventional energy sources are :

1. They do not pollute the atmosphere.
2. They are available in large quantities.
3. They are well suited for decentralised use.

According to energy experts the non-conventional energy sources can be used with advantage for *power generation* as well as other applications in a large number of locations and situations in our country.

10.2. WIND POWER PLANTS

10.2.1. Introduction

- **Wind** *is air set in motion by small amount of insolation reaching the upper atmosphere of earth.*
  - — Nature generates about 1.67 × 10^5 kWh of wind energy annually over land area of earth and 10 times this figure over the entire globe.
  - — Wind contains *kinetic energy* which can easily be *converted to electrical energy.*
- The wind energy, which is an indirect source of energy, can be used to run a wind will which in turn drives a generator to produce electricity. Although wind mills have been used for more than a dozen centuries for grinding grain and pumping water, interest in large scale power generation has developed over the past 50 years. A largest wind generator built in the past was 800 kW unit operated in France from 1958–60. The flexible 3 blades propeller was about 35 m in diameter and produced the rated power in a 60 km/hour wind with a rotation speed of 47 r.p.m. The maximum power developed was 12 MW. In India the interest in the wind mills was shown in the last fifties and early sixties. Apart from importing a few from outside, new designs were also developed, but these were not sustained. It is only in last 15–20 years that development work is going on in many institutions. An important reason for this lack of interest in wind energy must be that wind, in India is *relatively low and vary appreciably with seasons. These low and seasonal winds imply a high cost of exploitation of wind energy. In our country high wind speeds are however available in coastal areas of Sourashtra, Western Rajasthan and some parts of central India. In these areas there could be a possibility of using medium and large sized wind mills for generation of electricity.*

Applications of wind plants :

Following are the main *applications* of wind plants :

1. Electrical generation.
2. Pumping.
3. Drainage.
4. Grinding grains.
5. Saw milling.

10.2.2. Characteristics of Wind

The main characteristics of wind are :

- *Wind speed increases roughly as* $\frac{1}{7}$*th power of height. Typical* tower heights are about 20–30 m.
- *Energy-pattern factor.* It is the ratio of the actual energy in varying wind to energy calculated from the cube of mean wind speed. This factor is always *greater than unity* which means that energy estimates based on mean (hourly) speed are pessimistic.

10.2.3. Advantages and Disadvantages of Wind Energy

Following are the *advantages* and *disadvantages* of wind energy :

Advantages :

1. It is a renewable energy source.
2. Wind power systems being non-polluting have no adverse effect on the environment.
3. Fuel provision and transport are not required in wind energy conversion systems.
4. Economically competitive.

5. Ideal choice for rural and remote areas and areas which lack other energy sources.

Disadvantages :

1. Owing to its irregularity, the wind energy needs storage.
2. Availability of energy is fluctuating in nature.
3. The overall weight of a wind power system is relatively high.
4. Wind energy conversion systems are noisy in operation.
5. Large areas are required for installation/operation of wind energy systems.
6. Present systems are neither maintenance free, nor practically reliable.
7. Low energy density.
8. Favourable winds are available only in a few geographical locations, away from cities, forests.
9. Wind turbine design, manufacture and installation have proved to be most complex due to several variables and extreme stresses.
10. Requires energy storage batteries and/or stand by diesel generators for supply of continuous power to load.
11. Wind farms require flat, vacant land free from forests.
12. Only in kW and a few MW range ; it does not meet the energy needs of large cities and industry.

10.2.4. Sources/Origins of Wind

Following are the two sources/origins of wind (a natural phenomenon) :

1. Local winds.
2. Planetary winds.

1. **Local winds.** These winds are caused by *unequal heating and cooling of ground surfaces and ocean/lake surfaces during day and night.* During the day warmer air over land rises upwards and colder air from lakes, ocean, forest areas, shadow areas flows towards warmer zones.

2. **Planetary winds.** These winds are caused by *daily rotation of earth around its polar axis and unequal temperature between polar regions and equatorial regions.* The strength and direction of these planetary winds change with the seasons as the solar input varies.

- Despite the wind's intermittent nature, *wind patterns at any particular site remain remarkably constant year by year.*
- Average wind speeds are greater in hilly and coastal areas than they are well in land. The winds also tend to blow more consistently and with greater strength over the surface of the water where there is a less surface drag.
- *Wind speeds increase with height*. They have traditionally been measured at a standard height of 10 metres where they are found to be 20–25 per cent greater than close to the surface. At a height of 60 m they may be 30–60 per cent higher because of the reduction in the drag effect of the surface of the earth.

10.2.5. Wind Availability and Measurement

Wind energy can only be economical in areas of good wind availability. Wind energy differs with region and season and also, possibly to an even greater degree with local terrain and vegetation. Although wind speeds generally increase with height, varying speeds are found over different kinds of terrain. Observations of wind speed are carried out at meteorological stations, airports and lighthouses and are recorded regularly with ten minute mean values being taken every three hours at a height of 10 m. But airports, sometimes are in valleys and many wind speed meters are situated low and combinations of various, other factors mean that reading can be misleading. It is difficult, therefore, to determine the real wind speed of a certain place without actual in-situ measurements.

The World Meteorological Organization (WMO) has accepted four methods of wind recording :

(*i*) Human observation and log book.

(*ii*) Mechanical cup-counter anemometers.

(*iii*) Data logger.

(*iv*) Continuous record of velocity and direction.

1. **Human observation and log book.** This involves using the Beaufort Scale of wind strengths which defines visible "symptoms" attributable to different wind speeds. The method is *cheap* and *easily implemented* but is *often unreliable*. The best that can be said of such records is that they are better than nothing.

2. **Mechanical cup-counter anemometers.** The majority of meteorological stations use mechanical cup-counter anemometers. By taking the readings twice or three times a day, it is possible to estimate the mean wind speed. This is a *low cost method*, but is *only relatively reliable*. The instrument has to be in good working order, it has to be correctly sited and should be reliably read at least daily.

3. **Data logger.** The equipment summarizes velocity frequency and direction. It is *more expensive and prone to technical failures but gives accurate data*. The method is tailored to the production of readily interpretable data of relevance to wind energy assessment. It does not keep a time series record but *presents the data in processed form*.

4. **Continuous record of velocity and direction.** This is how data is recorded at major airports of

permanently manned meteorological stations. The *equipment is expensive and technically complex*, but it retains a detailed times-series record (second-by-second) of wind direction and wind speed. Results are given in copious quantities of data which require lengthy and expensive analysis.

10.2.6. Wind Power

The wind power can be computed by using the concept of kinetics. The mind mill works on the principle of *converting kinetic energy of the wind to mechanical energy.*

"Power density" in moving air is given by

$$P_w = KU_w^3 \; W/m^2 \qquad \text{...(10.1)}$$

where, U_w = Wind speed in km/h, and

$K = 1.3687 \times 10^{-2}$

Theoretically a fraction $\frac{16}{27} = 0.5926$ of the power in the wind is recoverable. This is called *Gilbert's limit* or *Betz coefficient.* Aerodynamically efficiency for converting wind energy to mechanical energy can be reasonably assumed to be 70 per cent. So the mechanical energy available at the rotating shaft is limited to 40 per cent or at the most 45 per cent of wind energy.

- Available wind power (P_a) may be given as :

$$P_a = \frac{1}{2} mU_w^2 = \frac{1}{2} \,.\, \rho.A.U_w U_w^2 = \frac{1}{2}\, \rho.\, \frac{\pi}{4}\, D^2.U_w^3$$

$$= \frac{1}{8}\, \rho \pi D^2 U_w^3 \text{ watts} \qquad \text{...(10.2)}$$

where, ρ = Density of air (1.225 kg/m^3 at sea level), and

D = Diameter (in meters), in *horizontal axis* aeroturbines.

Eqn. (10.2) indicates that maximum power available from the wind *varies according to square of the diameter* of the intercept area (or square of the root diameter) normally taken to be swept area of the aeroturbine. The combined effects of wind speed and rotor diameter variations is shown in Fig. 10.1. Thus, *wind machines intended for generating substantial amounts of power should have large rotors and be located in areas of high wind speeds.*

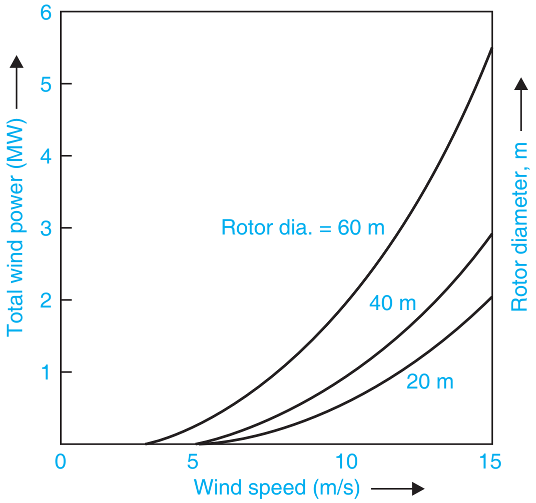


Fig. 10.1. The combined effects of variations of wind speed and diameter.

- State-wise wind power potential and wind power addition capacity (as on 31-12-2004) are given in Table 10.1 and Table 10.2 respectively.

Table 10.1. Wind Power Potential

State	*Gross potential(MW)* *(a)*	*Technical potential (MW)* *(b)*
Andhra Pradesh	8275	1750
Gujarat	9675	1780
Karnataka	6620	1120
Kerala	875	605
Medhya Pradesh	5500	825
Maharashtra	3650	3020
Odisha	1700	680
Rajasthan	5400	895
Tamil Nadu	3050	1750
West Bengal	450	450
Total	**45195**	**12875**

Table 10.2. State-wise Wind Power Capacity Addition (As on 31-12-2004)

State	*Demonstration projects (MW) (a)*	*Private sector projects (MW) (b)*	*MW (Total) capacity (MW) (a) + (b)*
Andhra Pradesh	5.4	95.9	101.3
Gujarat	17.3	202.6	219.9
Karnataka	7.1	268.9	276.0
Kerala	2.0	0.0	2.0
Madhya Pradesh	0.6	27.0	27.6
Maharashtra	8.4	402.8	411.2
Rajasthan	6.4	256.8	263.2
Tamil Nadu	19.4	1658.0	1677.4
West Bengal	1.1	0.0	1.1
Others	0.5	0.0	0.5
Total	**68.2**	**2912.0**	**2980.2**

Characteristics of a good wind power site :

A good wind power site should have the following *characteristics* :

1. High annual wind speed.
2. An open plain or an open shore line.
3. A mountain gap.
4. The top of a smooth, well rounded hill with gentle slopes lying on a flat plain or located on an island in a lake or sea.
5. There should be no full obstructions within a radius of 3 km.

10.2.7. Terms and Definitions

1. **Aerodynamics.** It is the branch of science which deals with air and gases in motion and their mechanical effects.
2. **Wind.** Air in motion.
3. **Windmill.** It is the machinery driven by the wind acting upon sails used chiefly in flat districts for grinding of corn, pumping of water etc.
4. **Wind turbine (Aeroturbine, wind machine).** It is a machine which converts wind power into rotary mechanical power. A wind turbine has aerofoil blades mounted on the rotor. The wind drives the rotor and produces rotary mechanical energy.
5. **Wind turbine generator unit.** It is an assemblage of a wind turbine, gear chain, electrical generator, associated civil works and auxiliaries.
6. **Wind farm (wind energy park).** It is a zone comprising several turbine-generator units, electrical and mechanical auxiliaries, substation, control room etc.

   Wind farms are located in areas having continuous favourable wind. Such locations are on-shore or off-shore away from cities and forests.
7. **Nacelle.** It is an assemblage comprising of the wind turbine, gears, generator, bearings, control gear etc. mounted in a housing.
8. **Propeller (wheel).** It is a revolving shaft with blades. The blades are set at an angle and twisted (like thread of a screw).
9. **Hub.** It is control solid part of the wheel (propeller).
10. **Pitch angle.** It is the angle between the direction of wind and the direction perpendicular to the planes of blades.
11. **Pitch control.** It is the control of pitch angle by turning the blades or blade tips [Fig. 10.2 (*a*)].
12. **Yaw control.** It is the control for orienting (steering) the axis of wind turbine in the direction of wind [Fig. 10.2 (*b*)].
13. **Teethering.** It is see-saw like swinging motion with hesitation between two alternatives. The plane of wind turbine wheel is swung in inclined position at higher wind speeds by teethering control [Fig. 10.2 (*b*)].

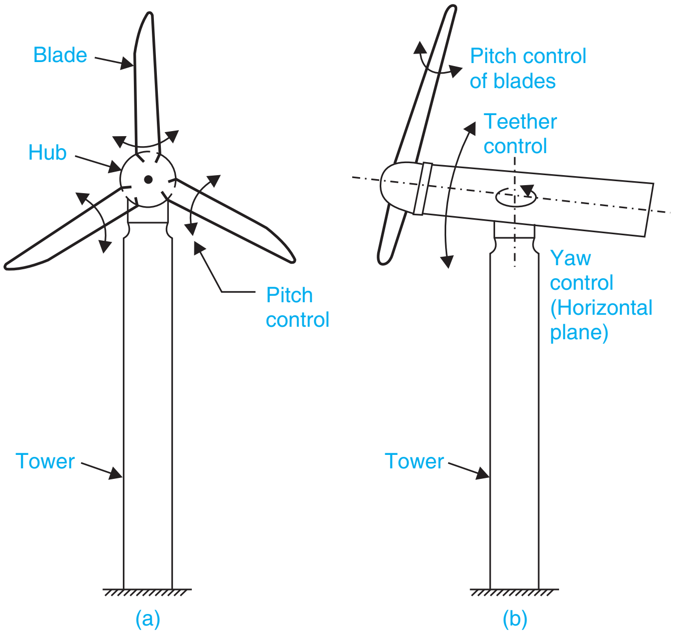


Fig. 10.2. Controls in wind-turbines: Pitch control; Yaw control ; Teether control.

14. **Wind speeds for turbines :**

(*i*) ***Cut-in-speed.*** It is the wind speed at which wind-turbine starts delivering shaft power. For a typical horizontal shaft propeller turbine it may be around 7 m/s.

(*ii*) ***Mean wind speed.***

$$U_{wm} = \frac{U_{w_1} + U_{w_2} + \cdots\cdots + U_{w_n}}{n}$$

(*iii*) ***Rated wind speed.*** It is the velocity at which the wind-turbine generator delivers rated power.

(*iv*) ***Cut-out wind velocity (furling wind velocity).*** It is the speed at which power conversion is cut-out.

10.2.8. Types of Wind Mills

The various types of wind mills (Fig. 10.3) are :

1. Multiple blade type.
2. Savonius type.
3. Darrieus type.

1. **Multiple blade type.** It is the *most widely used* wind mill.

- It has 15 to 20 blades made from metal sheets. The *sail type* has three blades made by stitching out triangular pieces of convass cloth. Both these types run at low speeds of 60 to 80 r.p.m.

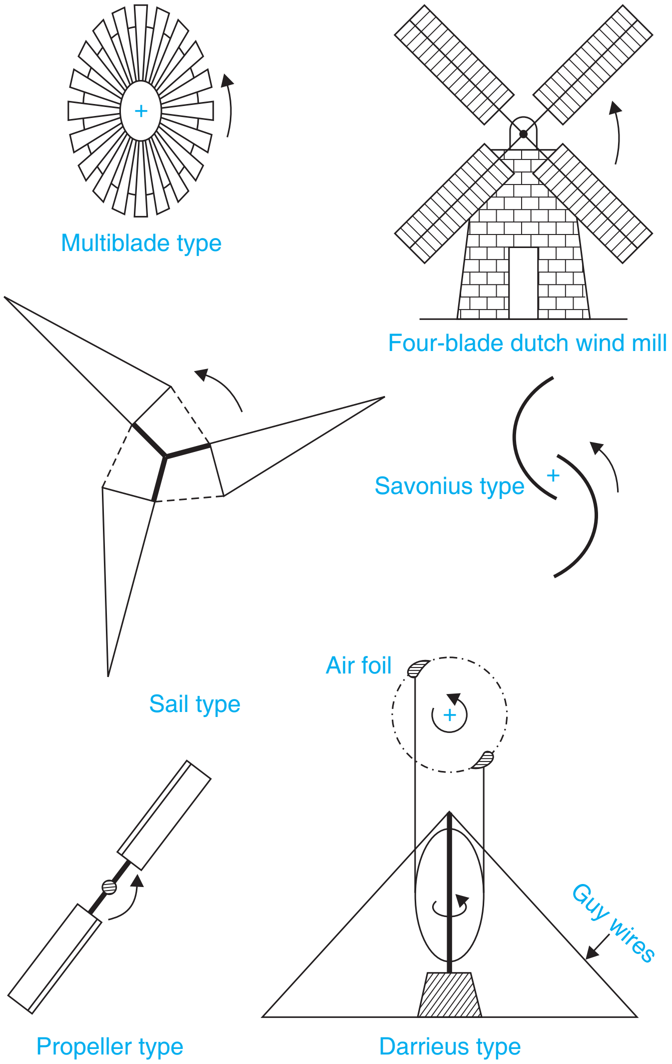


Fig. 10.3. Types of wind mills.

2. **Savonius type.** This type of windmill has hollow circular cylinder sliced in half and the halves are mounted on vertical shaft with a gap in between.

- Torque is produced by the pressure difference between the two sides of the half facing the wind.
- This is quite efficient but needs a large surface area.

Characteristics of savonius rotor :

(*i*) Self starting.

(*ii*) Low speed.

(*iii*) Low efficiency.

3. **Darrieus type.** This wind mill needs *much less surface area.*

- It is shaped like an egg beater and has two or three blades shaped like aerofoils.

Characteristics of Darrieus rotor :

(*i*) Not self starting.

(*ii*) High speed.

(*iii*) High efficiency.

(*iv*) Potentially low capital cost.

It may be noted that :

- Both the Savonius and Darrieus types are mounted on a *vertical axis* and hence they *can run independently of the direction of wind*.
- The horizontal axis mills *have to face the direction of the wind* in order to generate power.

Performance of Wind mills :

The performance of a wind mill is defined as *'Co-efficient of performance'* (K_p).

$$K_p = \frac{\text{Power delivered by the rotor}}{\text{Maximum power available in the wind}}$$

or $$K_p = \frac{P}{P_{max}} = \frac{P}{\frac{1}{2}\rho A U_w^3}$$

where, ρ = Density of air,

A = Swept area, and

U_w = Velocity of wind.

Fig. 10.4 shows a plot between K_p and tip speed ratio U_{bt}/U_w

where, U_{bt} = Speed of blade tip.

It can be seen that K_p is the *lowest of Savonius* and *Dutch types* whereas the *propeller types have the highest value*.

In the designing of wind mills, it is upper most to keep the *power to weight ratio at the lowest possible level.*

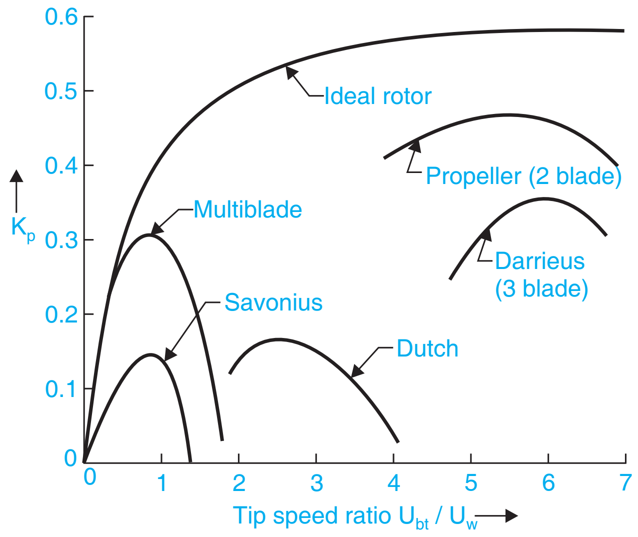


Fig. 10.4. K_p of wind mills.

10.2.9. Wind-electric Generating Power Plant

Fig. 10.5 shows the various parts of a wind-electric generating power plant. These are :

1. Wind turbine or rotor
2. Wind mill head—it houses speed increaser, drive shaft, clutch, coupling etc.
3. Electrical generator
4. Supporting structure

— The most important component is the **rotor.** For an effective utilisation, all components should be properly designed and matched with the rest of the components.

— The wind mill head performs the following functions :

(*i*) It supports the rotor housing and the rotor bearings.

(*ii*) It also houses any control mechanism incorporated like changing the pitch of the blades for safety devices and tail vane to orient the rotor to face the wind, the latter is facilitated by mounting it on the top of the supporting structure on suitable bearings.

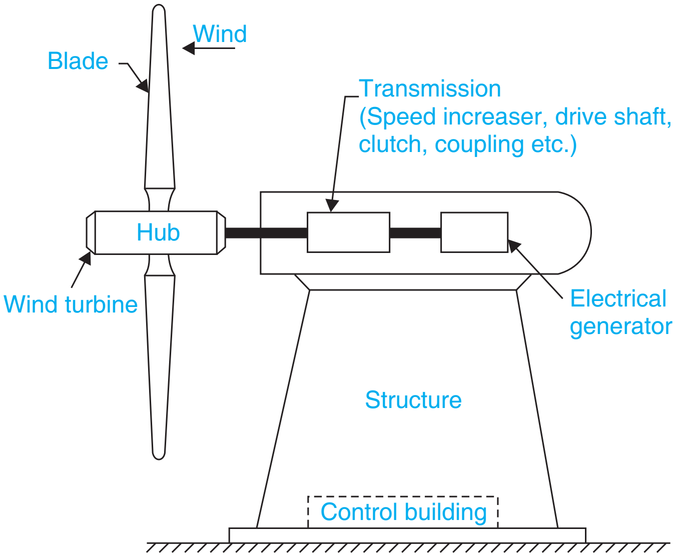


Fig. 10.5. Wind-electric generating power plant.

— The wind turbine may be located either *unwind* or *downwind* of the power. In the unwind location the wind encounters the turbine before reaching the tower. *Downwind rotors are generally preferred especially for the large aerogenerators*.

— The **supporting structure** is designed to withstand the wind load during gusts. Its type and height is related to cost and transmission system incorporated. Horizontal axis wind turbines are mounted on towers so as to be above the level of turbulence and other ground related effects.

10.2.10. Types of Wind Machines

Wind machines (***aerogenerators***) are generally *classified* as follows :

1. Horizontal axis wind machines
2. Vertical axis wind machines.

1. **Horizontal axis wind machines.** Fig. 10.6 shows a schematic arrangement of a horizontal axis machine. Although the common wind turbine with a horizontal axis is simple in principle, yet the design of a complete system, especially a large one that would produce electric power economically, is complex. It is of paramount importance that the components like rotor, transmission, generator and tower should not only be as efficient as possible but they must also function effectively in combination.

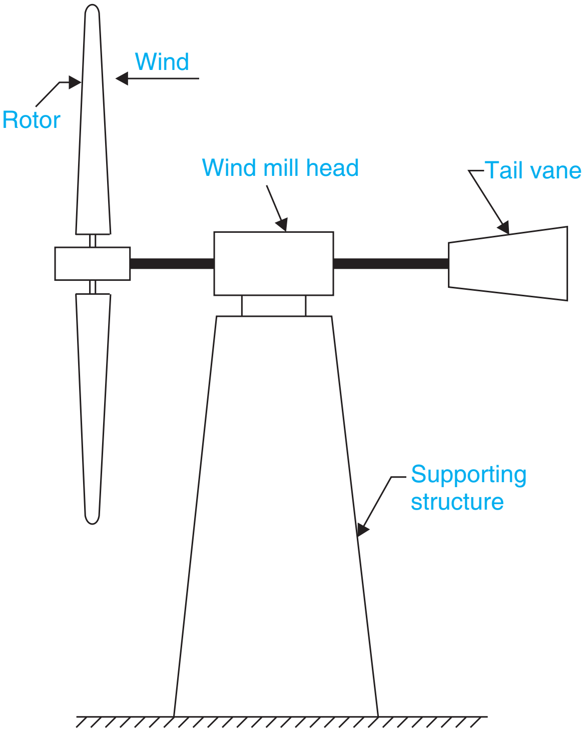


Fig. 10.6. Horizontal axis wind machine.

2. **Vertical axis wind machines.** Fig. 10.7 shows vertical axis type wind machine. One of the main advantages of vertical axis rotors is that they do not have to be turned into the windstream as the wind direction changes. Because their operation is independent of wind direction, vertical axis machines are called *panemones*.

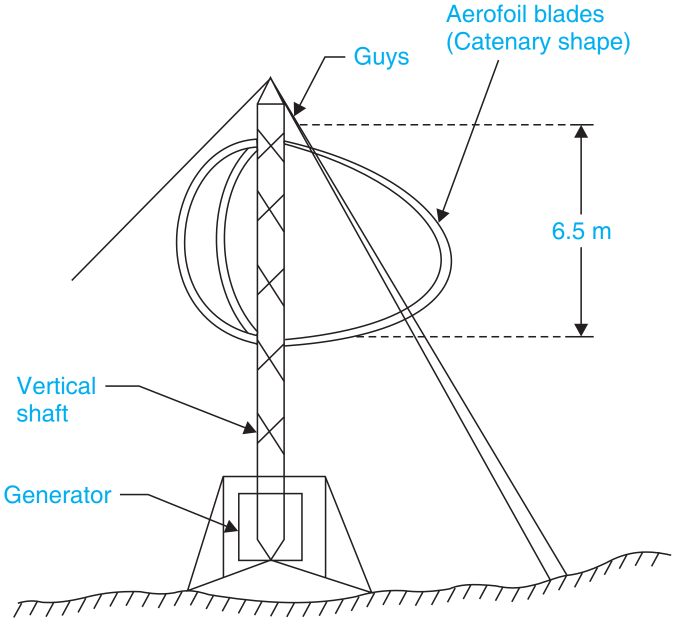


Fig. 10.7. Vertical axis wind machine.

Advantages of vertical axis wind machines :

1. The rotor is not subjected to continuous cyclic gravity loads since the blades do not turn end over end (Fatigue induced by such action is a major consideration in the design of large horizontal axis machines).
2. Since these machines would react to wind from any direction, therefore, they do not need yawing equipment to turn the rotor into the wind.
3. As heavy components (*e.g.* gear box, generator) can be located at ground level these machines may need less structural support.
4. The installation and maintenance are easy in this type of configuration.

10.2.11. Utilisation Aspects of Wind Energy

Utilisation aspects of wind energy fall into the following three broad categories :

1. Isolated continuous duty systems which need suitable energy storage and reconversion systems.
2. Fuel-supplement systems in conjunction with power grid or isolated conventional generating units.
    - This utilisation aspect of wind energy is the *most predominant in use as it saves fuel and is fast growing particularly in energy deficient grids.*

3. Small rural systems which can use energy when wind is available.
    - This category has application in *developing countries with large isolated rural areas.*

10.2.12. Generating Systems

The wind turbine-generator unit comprising wind turbine, gears and generator, converts wind power into electrical power. Several identical units are installed in a wind farm. The total electrical power produced by the wind farm is fed into the distribution network or stand alone electrical load.

The choice of electrical system for an aeroturbine is guided by *three* factors :

(*i*) ***Type of electrical output :***

— D.C.

— Variable-frequency A.C.

— Constant-frequency A.C.

(*ii*) ***Aeroturbine rotational speed :***

— Constant speed with variable blade pitch.

— Nearly constant speed with simpler pitch-changing mechanism.

— Variable speed with fixed pitch blades.

(*iii*) ***Utilisation of electrical energy output :***

— In conjunction with battery or other form of storage.

— Interconnection with power grid.

10.2.12.1. Constant speed-constant frequency (CSCF) system

Large scale electrical energy generated from wind is expected to be fed to the power grid to displace fuel generated kWh. For this application present economics and technological developments are heavily weighted in favour of CSCF system with alternator as the generating unit. It must be reminded here that to obtain high efficiencies the blade pitch varying mechanism and controls have to be installed.

— Wind turbines of electrical rating of *100 kW and above* are of constant-speed type and are coupled to synchronous generators (conventional type). The turbine rated at *less than 100 kW* is coupled to fairly constant speed induction generators connected to grid and so operating at constant frequency having their excitation VARs from the grid or capacitor compensators.

10.2.12.2. Variable speed-constant frequency (VSCF) system

Variable-speed drive is *typical for small wind generators* used in autonomous applications, generally producing variable frequency and variable voltage output.

The variable speed operation of wind electric system *yields higher outputs* for both low and high wind speeds. This results in higher annual energy yields per rated installed kW capacity. Both horizontal axis and vertical axis turbines will exhibit this gain under variable speed operation.

The following schemes are used *to obtain constant frequency output* :

(*i*) A.C.—D.C.—A.C. link.

(*ii*) Double output induction generator.

(*iii*) A.C. commutation generator.

With the advent of power switching technology (*viz* high power diodes and thyristors) and chip-based associated control circuitry, it has now become possible to use VSCF systems. VSCF and wind electrical systems and its associated power conditioning system operate as shown in Fig. 10.8.

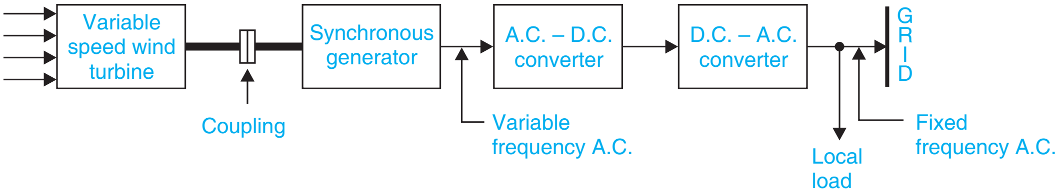


Fig. 10.8. Block schematic of VSCF wind electrical system.

VSCF wind electrical systems claim the following ***advantages*** :

1. Significant reduction in aerodynamic stresses, which are associated with constant-speed operation.
2. It is possible to extract extra energy in the high wind region of the speed-duration curve.
3. Complex pitch changing mechanism is not required.
4. Wind turbine/Aeroturbine always operates at maximum efficiency point (constant tip-speed ratio).

10.2.12.3. Variable speed-variable frequency (VSVF) system

The generator output is affected by the variable speed. The frequency of the induced voltage depends on the impedance of the load and speed of the prime mover. The variable voltage can be converted to constant D.C. using choppers or rectifier and then to constant A.C. by the inverters.

10.2.13. Wind-Powered Battery Chargers

One application of wind energy systems which is of considerable potential importance (to developing countries) is the use of small wind generators to charge batteries for powering lighting, radio communication and hospital equipment. Wind generators have been in use in Europe and North America since the 1920s, although their use declined considerably.

A battery charging system has to include the following :

(*i*) A wind powered generator

(*ii*) A converter

(*iii*) A container for the batteries.

Fig. 10.9 shows a set-up of wind powered battery charging system. It is worthnoting that 12 volt batteries, which are rechargeable using wind generators, can be used to power fluorescent tube lighting which is six times more efficient than tungsten filament lamps. Such lighting opens up a number of important development opportunities in areas which normally have no lighting.

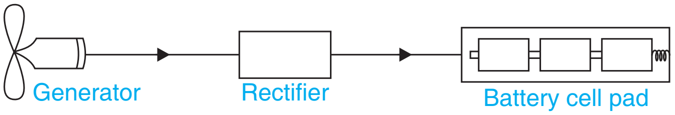


Fig. 10.9. Wind powered battery charging system.

For small wind generators the total system efficiency is made up as follows :

Wind regime matching efficiency	60% (approx.)
Rotor efficiency	35% (approx.)
Generator and wiring efficiency	70% (approx.)
Battery charge/discharge efficiency	70% (approx.)

Cumulatively, a total energy capture efficiency of about 10% is generally obtained from small wind generators utilized for battery charging.

Battery charging wind generators are produced in several countries, notably Australia, France, Sweden, Switzerland, the U.K., the U.S.A. and West Germany. In developing countries production is underway in China and has started in India.

10.2.14. Wind Electricity in Small Independent Grids

Refer to Fig. 10.10. In such systems electricity consumption fluctuates constantly as does the availability of wind energy. The degree of coincidence of supply and demand can be calculated by statistical means and it has been found that electricity supply with an acceptable degrees of reliability cannot be based solely on wind energy. If an extensive grid does not exist, electricity storage (batteries) or a back-up system (diesel) is required. Loads for remote systems of upto 6 kWh/day equivalent to an average power consumption of 250 W with a duty cycle of 24 hours, can be provided with battery storage.

If a diesel and wind generator are used in conjunction with a grid, the *diesel generator should only be used when wind energy is absent*. Problems can occur, however, when the diesel generator is called on to change its output frequently as wind energy availability fluctuates. Besides decreasing the oil saving, diesel generation on this basis leads to more frequent overhauls of the generator. Both factors will increase costs. Several methods of overcoming these problems have been tried but there is not yet an established solution. Some development work has still to be done before wind generators can be run in parallel with diesel on a routine basis.

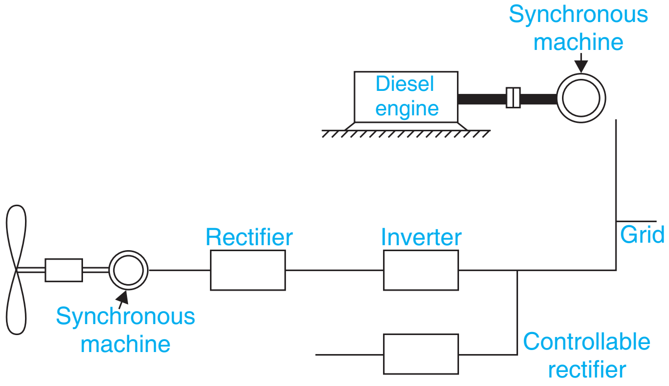


Fig. 10.10. Principle of combined wind/diesel power generation.

10.2.15. Wind Electricity Economics

Wind generator power costs are heavily linked to the characteristics of a wind resource in a specific location. The cost of supplied power declines as wind speeds increase, and the power supplied increases in proportion to the *cube of the wind speed*.

Matching available energy and load requirements is also important in wind energy economics. The correct size of wind generator must be chosen together with some kind of storage or co-generation with an engine or a grid to obtain the best economy. The ideal application is a task that can utilize a variable power supply, *e.g.* ice making or water purification.

Regarding the *economics*, the choice of interest rate obviously has a major effect on the overall energy cost. With low interest rates, capital intensive power sources such as solar and wind are favoured. Other factors bearing a strong influence on the economics of wind electricity are the standard of maintenance and service facilities and the cost of alternative energy supplies in the particular area.

10.2.16. Problems in Operating Large Wind Power Generators

The operation of large wind power generators entails the following *problems* :

1. **Location of site.** The most important factor is locating a site big enough which has a reasonable average high wind velocity.

Sourashtra and Coastal Regions in India are promising areas.

2. **Constant angular velocity.** A constant angular velocity is a must for generating A.C. (alternating current) power and this means very sensitive governing.

3. **Variation in wind velocity.** The wind velocity varies with time and varies in direction and also varies from the bottom to top of a large rotor (some rotors are as long as 50 metres). This causes fatigue in blades.

4. **Need of a storage system.** At zero velocity conditions, the power generated will be zero and this means some storage system will have to be incorporated along with the wind mill.

5. **Strong supporting structure.** Since the wind mill generator will have to be located at a height, the supporting structure will have to be designed to withstand high wind velocity and impacts. This will add to the initial costs of the wind mill.

6. **Occupation of large areas of land.** Large areas of land will become unavailable due to wind mill gardens (places where many wind mills are located). The whole area will have to be protected to avoid accidents.

Inspite of all these difficulties, interest to develop wind mills is there since this is a clean source of energy.

10.2.17. Considerations for Selection of Site for Wind Energy Conversion Systems

Following factors should be given due considerations while selecting the site for wind energy conversion systems :

1. Availability of anemometry data.
2. High annual average wind speed.
3. Availability of wind curve at the proposed site.
4. Wind structure at the proposed site.
5. Altitude of the proposed site.
6. Terrain and its aerodynamic.
7. Local ecology.
8. Distance to roads or railways.
9. Nearness of site to local centre/users.
10. Favourable land cost.
11. Nature of ground.

10.3. TIDAL POWER PLANTS—OCEAN ENERGY CONVERSION

10.3.1. Ocean Energy Sources—General Aspects

Ocean energy sources may be broadly divided into the following *four* categories :

1. Tidal energy.
2. Wave energy.
3. *Ocean thermal energy conversion (OTEC).
4. Energy emanated from the sun-ocean system from the mechanism of surface water evaporation by solar heating *i.e.*, hydrological cycle.

10.3.2. Tidal Power Plants

10.3.2.1. Introduction

The periodic rise and fall of the water level of sea which are carried by the action of the sun and moon on water of the earth is called the ***'tide'.***

- Tidal energy can furnish a significant portion of all such energies which are renewable in nature. The large scale up and down movement of sea water represents an unlimited source of energy. If some part of this vast energy can be converted into electrical energy, it would be an important source of hydropower.
- The *main feature of the tidal cycle is the difference in water surface elevations at the high tide and at the low tide.* If this differential head could be utilized in operating a hydraulic turbine, the tidal energy could be converted into electrical energy by means of an attached generator.

Tidal power :

When a basin exists along the shores with high tides, the power in the tide can be hydro-electrically utilised. This can be realised by having a long dam across the basin and locating two sets of turbines underneath the dam. As the tide comes in water flows into the basin one set of turbines. At low tide the water flows out of the basin operating another set of turbines.

Let,

h = Tidal range from high to low (in m), and

A = Area of water stored in the basin (in m^2).

Then, *energy stored* in the full basin is given as :

$$E = \rho g A \int_0^h x.dx$$

or,

$$E = \frac{1}{2} \rho g h^2 A \qquad ...(10.3)$$

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*The ocean thermal energy concept was proposed as early as 1881 by the French physicist Jacques d' Arsonval.

Average power,

$$P_{av.} = \frac{1}{2}\rho g h^2 A \Big/ \left(\frac{T}{2}\right) = \rho g h^2 \Big/ \left(\frac{A}{T}\right) \qquad ...(10.4)$$

where, T = Period of tidal cycle = 14 h 44 min, usually.

- Following are a few places which have been surveyed in the *world* as sites for tidal power :
  (*i*) San Jose (S. America) : 10.7 m, 777 km^2, 19,900 MW ;
  (*ii*) Sever (UK) : 9.8 m, 70 km^2, 8,000 MW ;
  (*iii*) Passanaquoddy Bay (N. America) : 5.5 m, 262 km^2, 1,800 MW.

In *India*, following are the major sites where preliminary investigations have been carried out :

(*i*) Bhavanagar ;
(*ii*) Navalakh (Kutch) ;
(*iii*) Diamond harbour ;
(*iv*) Ganga Sagar.

The basin in Kandla in Gujarat has been estimated to have a capacity of 600 MW.

— The total potential of Indian coast is around 9000 MW, which does not compare favourably with the sites in the American continent stated above. The technical and economic difficulties still prevail.

10.3.2.2. Components of tidal power plants

The following are the components of a tidal power plant :

1. The dam or dyke (low wall) to form the pool or basin.
2. Sluice ways from the basins to the sea and *vice versa*.
3. The power house.

Dam or dyke. The function of dam or dyke is to form a barrier between the sea and the basin or between one basin and the other in case of multiple basins.

Sluice ways. These are used to fill the basin during the high tide or empty the basin during the low tide, as per operational requirement. These devices are controlled through gates.

Power house. A power house has turbines, electric generators and other auxiliary equipment. As far as possible the power house and sluice ways should be in *alignment* with the dam or dyke.

10.3.2.3. Classification and operation of tidal power plants

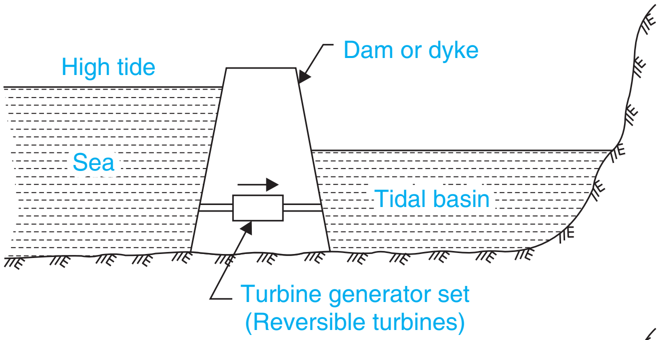
Tidal power plants are classified as follows :

1. **Single basin arrangement**

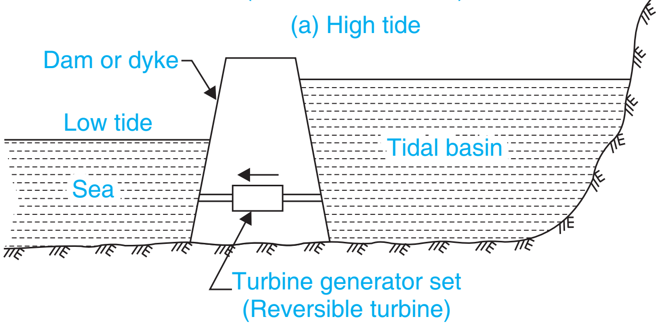
(*i*) Single ebb-cycle system
(*ii*) Single tide-cycle system
(*iii*) Double cycle system.

2. **Double basin arrangement.**

In a *single basin arrangement* power can be generated only *intermittently*. In this arrangement only one basin interacts with the sea. The two are separated by a dam or dyke and the flow between them is through sluice ways located conveniently along the dam. The rise and fall of tidal water levels provide the potential head.



(a) High tide



(b) Low tide

Fig. 10.11. General arrangement of tidal power plant.

Fig. 10.11 shows a general arrangement of single basin tidal power plant (double cycle system). Such plants generally use *reversible water turbines* so that power is generated on low tide as well high tide. The operation of the plant is as follows :

When the incoming tide sea level and tidal-basin level are equal, the turbine conduit is closed. When the sea level rises, and about half way to high tide the turbine valves are opened and the sea water flows into the basin through the turbine runner generating power. This also raises the level of water in the basin. The turbine continues to generate power until the tide passes through its high point and begins to drop. The water head then quickly diminishes till it is not enough to supply the no-load losses. By pass valve then quickly opens to let water into the basin to gain maximum water level. When sea and basin water level are again equal, the valves are closed as well as the turbine conduit. The basin level then stays constant while the tide continues to go out. After sufficient head has developed, the turbine valves are again opened and water