Elements of Electrical Power Station Design By MV Deshpande Phd
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Karl Bogha 13 May 2016
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Elements of Electrical Power Station Design
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Chapter 8
Example Problem 8.6 Page 227.

At a site for hydro-electric power project, a flow of 90m^3/s is available at a head of 100m. Sufficient storage is available. A hydro-electric power plant is to be chosen for the project.

Load factor of power system supplied by the station 80%
Cost of the hydro development $1500 per kW installed
Fixed cost 9%
Operation and maintenance cost $7 per kW per yr
Load centre is 80km from power station
Transmission line voltage to load centre 110kV
Transmission liability $20 per kW per yr
Energy used in generating stations for auxiliaries 2%

Efficiency of turbines 89.5%
Efficiency of generators 95

$Q := 90$ m^3/s discharge rate

$w := 1000$ kg/m^3 density of water

$n_t := 0.895$ efficiency of turbine(s)

$h := 100$ m head

a) Find the power that could be developed, the number of units required, and the capacities of the turbines and generators. Efficiency of turbines 89.5% and generators 95%

Power that could be developed:

$P_t := \frac{(Q \cdot w \cdot h \cdot n_t)}{75}$ $P_t = 107.4 \cdot 10^3$ metric hp

$Load\_Factor := 80\%$ Load Factor = Average load / Maximum load

80% load factor does not show much variation of load.
So 2 turbines can be chosen for the power station each carrying Pt/2.

$Turbine\_load := \frac{P_t}{2}$ $Turbine\_load = 53.7 \cdot 10^3$ metric hp

Generator capacity based on each turbine load:

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$One\_hp := 0.736$ kW   Converting hp to kW

$n_g := 0.95$ generator efficiency

$Generator\_capacity := Turbine\_load \cdot n_g \cdot One\_hp$

$Generator\_capacity = 37547.04$ kW ---> 37.547 MW

$P_{tot\_delivered} := 2 \cdot Generator\_capacity$

$P_{tot\_delivered} = 75094.08$ kW - 75.09 MW

b). Specifications for the turbines and generators

Each turbine output is 53,700 metric hp
Head at 100m
Turbine type: Use fixed blade Francis turbine.

Calculate the specific speed of the turbine(s):
Equation 8.4 - Francis Turbine page 208

$$n_s := \frac{6850}{(h + 9.8)} + 84 \qquad n_s = 146.386 \quad \text{rpm}$$

The corresponding actual speed:
Use equation 8.2 page 207

$P_{turb} := Turbine\_load$

$$n := \frac{n_s \cdot h^{\left(\frac{5}{4}\right)}}{P_{turb}^{\left(\frac{1}{2}\right)}} \qquad n = 199.762 \quad \text{rpm}$$

The synchronous speed of a generator is n=120f/p rev per min
f is the frequency, p is the number of poles. Use a 30 pole machine.

$f := 50$ Hz $p_{pole} := 30$

$$n_g := 120 \cdot \frac{f}{p_{pole}} \qquad n_g = 200 \quad \text{rpm}$$

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Now returning to correcting the specific speed by rearranging equation 8.2

$$n_{s\_new} := \frac{n_g \cdot \left(P_{turb}^{\frac{1}{2}}\right)}{h^{\frac{5}{4}}}$$

$n_{s\_new} = 146.561$ manually entered to simplify calculation below with regards to units

n_s_new is not very much different from n_s calculated earlier

$$difference\_ns\_nsnew := \left|\frac{n_s - n_{s\_new}}{n_s}\right| = 0.0012$$

See page 223 paragraph 3 on vertical and horizontal shaft suggestions.

<u>A suitable generator specification:</u>

1. vertical axis
2. 36,500 kW minimum
3. 0.9 power factor
4. 41.67 kVA (36500/0.9=40,560VA)
5. 200 rpm
6. star connected stator
7. 11kV
8. 3 phase
9. 50Hz
10. 60 degree temperature rise
11. air cooling for small generator
12. exciter requirements see section 8.8.1 Exciters for hydro-generators; page 220

c). Calculate the main dimensions of the turbine units

Using Table 8.1 'Dimensions of 1 hp (metric) wheel operating under 1 meter of head for reaction turbines only'.

For specific speed ns of 146.6, interpolating for the correct dimensions

$$D_1 := 102 - \left(\frac{(102 - 78.5)}{180 - 135} \cdot (146.6 - 135)\right) = 95.942$$

$$D_2 := 94 - \frac{(94 - 83.5)}{180 - 135} \cdot (146.6 - 135) = 91.293$$

Calculate width of distribution WD:

$$WD := 17.8 + \frac{(19.5 - 17.8)}{180 - 135} \cdot (146.6 - 135) = 18.238$$

Calculate model ratio m:

$$m\_ratio := \frac{P_{turb}^{\frac{1}{2}}}{2.46 \cdot h^{\left(\frac{3}{4}\right)}} \qquad m\_ratio = 2.979$$

The final dimensions after calculating m:

$D_{1new} := D_1 \cdot m\_ratio = 286$ cm

$D_{2new} := D_2 \cdot m\_ratio = 272$ cm

$WD_{new} := WD \cdot m\_ratio = 54$ cm

d). Calculate main dimensions of generator unit(s):

The general expression for the output of a generator as developed in chapter 3, equation 3.23, holds for hydro-generators.

$B := 6.5 \cdot 10^{-5}$ weber/cm^2
$a_c := 400$ ampere conductors per centimeter of periphery

$n_{g\_seconds} := \frac{n_g}{60}$ rps (rev per second)

Rearranging eq. 3.23 to solve for (D^2)L

$S := \frac{36500}{0.9} = 40.56 \cdot 10^3$ kVA

$$D_{sqrd}L := \frac{S}{\left(10.4 \cdot 10^{-3}\right) \cdot B \cdot a_c \cdot n_{g\_seconds}} \qquad D_{sqrd}L = 44.995 \cdot 10^6 \quad \text{cm^3}$$

Let D^2(L) = x

Choose a core length L equal to pole pitch

D^2 = x/L

Also x = (pi)D/p

Now equate both x; x = D^2(L) = (pi)D/p

Rearranging xp/(pi)D = D^2(L)

D^3 = xp/(pi)

So $x := D_{sqrd} L = 44.995 \cdot 10^{6}$

$D_{cube} := \frac{x \cdot p_{pole}}{\pi}$ $D_{cube} = 429.671 \cdot 10^{6}$ cm^3

$D := \sqrt[3]{D_{cube}}$ $D = 754.6$ cm

Solving for L:

x/L = x(p)/(pi)D

L = (pi) D / p <-------- This is the pole pitch

$L := \pi \cdot \frac{D}{p_{pole}}$ $L = 79.021$ cm approximately

Calculate the peripheral speed:

$s_{peripheral} := \left(\pi \cdot D \cdot 10^{-2}\right) n_g$ D converted from cm to m, times 10^-2

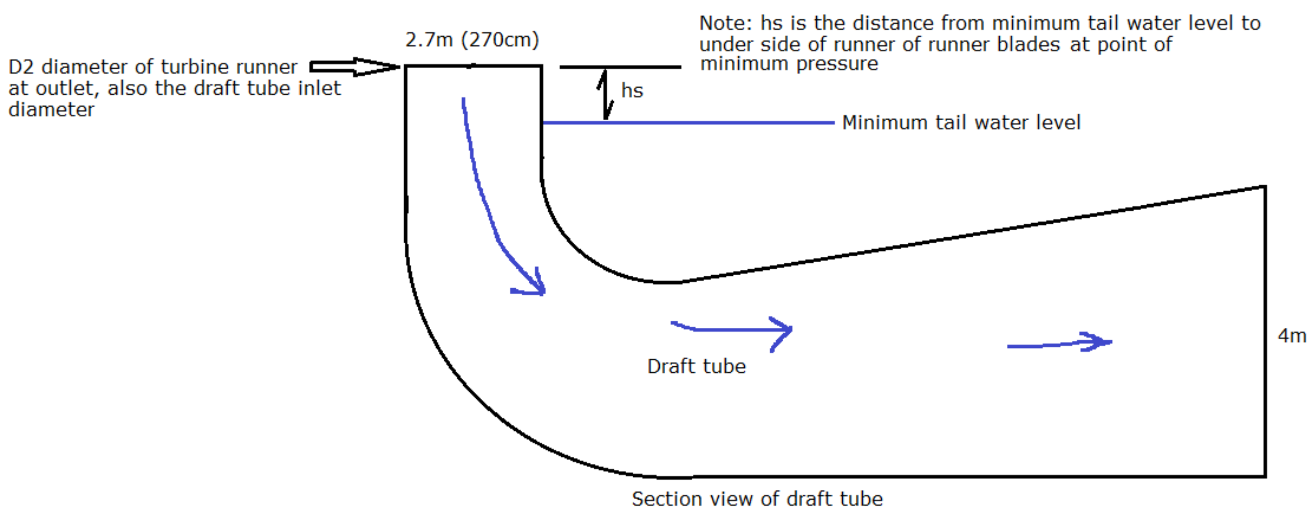
$s_{peripheral} = 4741.24$ m/min

Page 222 Paragraph 5- The peripheral speed limit
may be taken as between 3500 and 5000 m/min.

Peripheral speed at 4741.24 is between 3500 and 5000, so it is permissible.

$D = 755$ cm $L = 79$ cm

e). Determine the draft tube areas at inlet and outlet



Note: hs is the distance from tailwater to underside of runner blades at point of minimum pressure

The flow of 90m^3/s is divided by 2 since the discharge is split in two.

$Q_1 := \frac{Q}{2}$ $\qquad Q_1 = 45$

Diameter of turbine runner at outlet D2, is the diameter at inlet of draft tube.

$D_{2new} = 271.951$ cm

$D_{2\_m} := \left(\frac{D_{2new}}{100}\right) = 2.72$ convert to meters

Flow divided by area equal to velocity

Velocity at inlet of draft tube v2:

$v_2 := \frac{Q_1}{\left(\frac{\pi}{4}\right) \cdot D_{2\_m}^{\ 2}}$ $\qquad v_2 = 7.747$ m/s

Page 216 permissible velocities at inlet and outlet of draft tube:

For high specific speeds at outlet - -> 0.0325 sqrt(2gh)

Velocity at outlet of draft tube v3:

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$gravity := 9.81$ m/s^2

$h = 100$

$v_3 := 0.0325 \cdot \left(\sqrt{2 \cdot gravity \cdot h}\right) = 1.44$

For safety factor we will use --->0.003 sqrt(2gh)

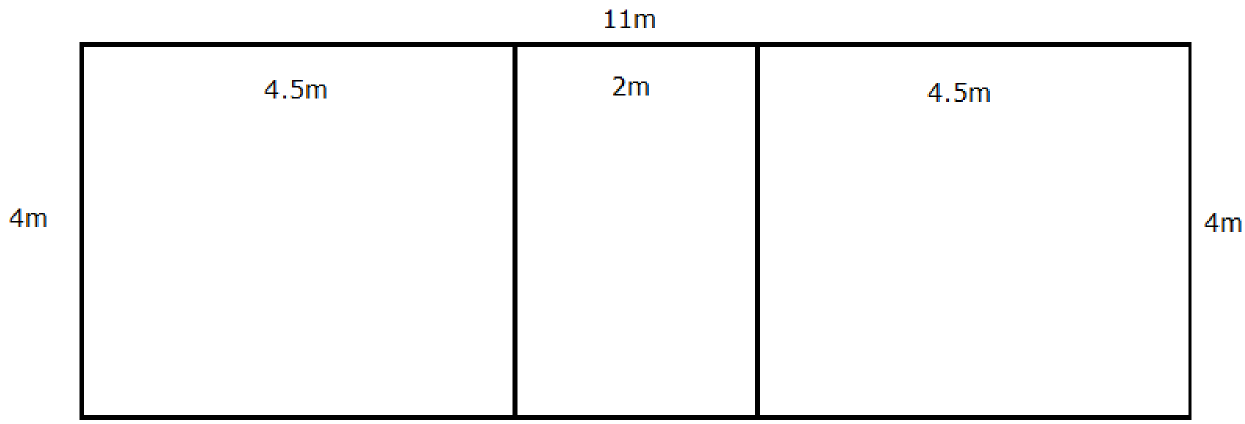
$v_3 := 0.03 \cdot \left(\sqrt{2 \cdot gravity \cdot h}\right) = 1.329$ m/s

Let v3 = 1.25m/s this will create a larger water exit cross section area
Area at exit = Q1/v3

$v_3 := 1.25$ m/s

$Area\_exit := \frac{Q_1}{v_3}$ $Area\_exit = 36$ m^2 Whole number and easily made into a square area with distances

We choose a cross section area of 4 x 6 meters
4m x 6m = 36m^2.
With a central pier of 2m wide. Pier is solid no flow thru it.
The draft tube end section dimension will be 4m x 11m.



End view (water discharged from draft tube)

Using a quarter turn draft tube. We have 2 sets of turbines and each has two flares. The discharge from the runner is flared into two. So for this power station with 2 sets of turbines there are a total of 4 flares.

Length of draft tube:

$L\_draft\_tube\_at\_exit := 11$ m

$L\_draft\_tube\_inlet := D_{2\_m} = 2.72$ m

$$Length\_draft\_tube := \left(\frac{L\_draft\_tube\_at\_exit - L\_draft\_tube\_inlet}{2}\right) \cdot 4$$

$Length\_draft\_tube = 16.561$ 4 tubes in parallel total length

f). Determine the setting of the turbine, hs, with respect to the tail water

$n_s = 146.386$

Use figure 8.13a for obtaining the cavitation coefficient; page 216.
Cavitation Coefficient = 0.065, use 0.0724 as made known in textbook example.
Minor change in coefficient results in significant difference in hs.

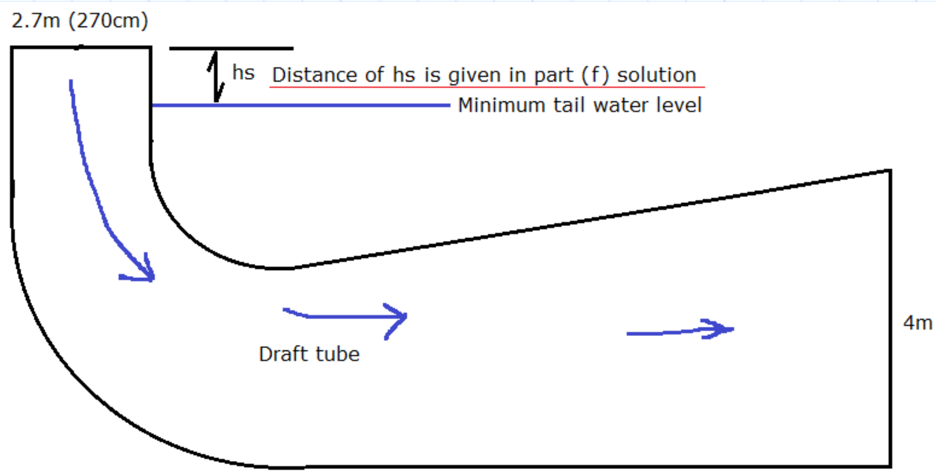
$\sigma := 0.0724$

hb is the barometric pressure head at elevation of runner above mean sea-level

$h_b := 7.62$ m

$h_s := h_b - (\sigma \cdot h) = 0.38$ m

The turbine is set at 0.38 meters above the tail water level.
See figure 8.2 (top) page 201.

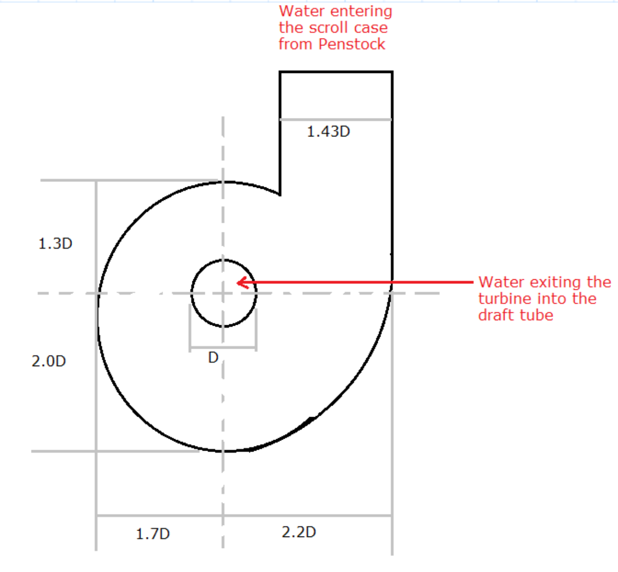


Section view of draft tube

g). Find the approx. dimensions of scroll case for each unit:

The scroll case is generally made of plate steel. Its purpose is convert the pressure head gradually into higher velocities, before water enters the turbine runner. Its dimension are related to a certain extent to the inlet diameter of the draft tube or the outlet diameter of the turbine runner.

See the figure below for the scroll case dimension sizing.



Plan view of scroll case

Diameter D in figure above is the draft tube inlet diameter D2 in meters.

$D_{2\_m} = 2.72$

$1.47 \cdot D_{2\_m} = 3.998$

$1.30 \cdot D_{2\_m} = 3.535$

$2.00 \cdot D_{2\_m} = 5.439$

$1.7 \cdot D_{2\_m} = 4.623$

$2.2 \cdot D_{2\_m} = 5.983$

h). Determine the main dimensions of penstock for each unit:

Velocity through each penstock allowed is between 2 to 6 m/s
So for this problem velocity through penstock of 4m/s

There are 2 penstocks, with each having 2 flared draft tubes.

Area of penstock from flow and velocity:

$v_{pen} := 4$ m/s $Q_1 = 45$

$Area\_penstock := \frac{Q_1}{v_{pen}}$ $Area\_penstock = 11.25$ m^2

Diameter of penstock = Sqrt(Area x 4)/pi

$$D_{pen} := \sqrt{\frac{(Area\_penstock \cdot 4)}{\pi}}$$

$D_{pen} = 3.785$ m $D_{pen\_cm} := D_{pen} \cdot 100 = 378.47$ cm

Thickness of penstock t = (0.1 x h x d)/((2 x f x nj)

t = thickness of penstock
h = head in meters
d = diameter of penstock in cm
nj = joint efficiency
f = permissible stress in kg/cm^2

Permissible stress f 950kg/cm^2 with static head alone
If water hammer is included f is 1125kg/cm^2
Joint efficiency if riveted 80%, if welded up to 90%

$f_{stress\_cm} := 1000$ kg/cm^2 $n_j := 90\%$ $h_{cm} := h \cdot 100 = 1 \cdot 10^4$ cm

All the units are in cm

$t := \frac{(0.1 \cdot h \cdot D_{pen\_cm})}{2 \cdot f_{stress\_cm} \cdot n_j}$ $t = 2.103$ cm

Adding for corrosion of 0.15cm

$Corr_{adj} := 0.15$ cm $t_{final} := t + Corr_{adj} = 2.253$

The penstock diameter is 348.47cm and thickness is 2.25 cm.

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i). Suggest a preliminary plan layout of the station units,
and find the approximate dimensions of the main floor of the buildings

Using figure 8.14 page 224, with ns = 146 rpm , X is approximately equal to 4.75

$X := 4.75$

$Dist_{cntr\_cntr} := D_{2\_m} \cdot X$

$Dist_{cntr\_cntr} = 12.918$

Make it a whole number for the distance, manual entry below

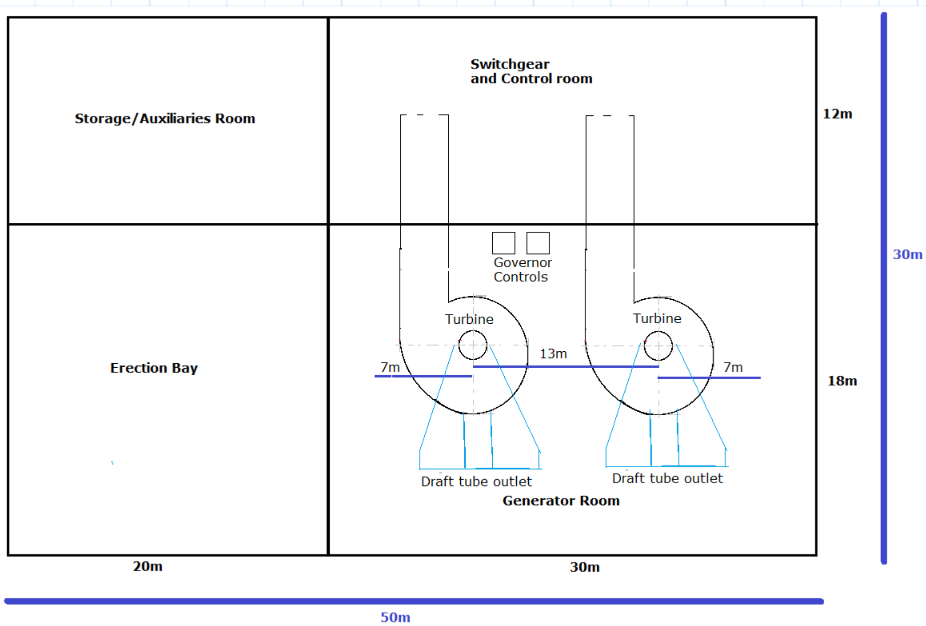
$Dist_{cntr\_cntr} := 13$ m

Lets do a check from the scroll case major dimensions, and allowing at least 2m between units:

$1.7 \cdot D_{2\_m} + 2.2 \cdot D_{2\_m} + 2 = 12.606$

The distance can be set at 13m.

Applying the distances of the scroll case, generator spacings, space to work around equipment, with erection bay 1.5 times the operations bay, the final room size is shown in the figure below at 50m x 30m. Its an approximation intended for preliminary design.



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j). Find the cost of energy per kilowatt-hour at the load centre from the data given below.

Load factor of power system supplied by the station 80%
Cost of the hydro development $1500 per kW installed
Fixed cost 9%
Operation and maintenance cost $7 per kW per yr
Load centre is 80km from power station
Transmission line voltage to load centre 110kV
Transmission liability $20 per kW per yr
Energy used in generating stations for auxiliaries 2%

Efficiency of turbines 89.5%
Efficiency of generators 95

Set the variables below:

$LF := 0.8$ ie 80%
$Cost_{dev\_perkw} := 1500$
$Fixed_{costperkw} := 0.09$ ie 9%
$OperMant\_Cost_{perkwperyr} := 7$
$Load\_Cntr\_dist := 80$
$TransLine\_volt := 110000$
$TransLineLiability_{perkwperyr} := 20$
$Aux\_Energy := 0.02$ ie 2%

$P_{tot\_delivered} = 75.094 \cdot 10^{3}$ kW 75.095 MW

From calculations earlier the total capacity of the power station is 75000 kW (75 MW)

$PwrSt\_capacity := 75000$ kw Here we want to keep the numeral at kW because the costs are rated at per kW (75,000 <--kW)

The fixed cost is the 9% of the capital cost per kw of the total power capacity

$FixedCost\$:= Fixed_{costperkw} \cdot Cost_{dev\_perkw} \cdot PwrSt\_capacity$

$FixedCost\$ = 10.13 \cdot 10^{6}$ Fixed cost is 9% of capital cost

$OperMaintenanceCost\$:= OperMant\_Cost_{perkwperyr} \cdot PwrSt\_capacity$

$OperMaintenanceCost\$ = 525 \cdot 10^{3}$ Cost to operate and maintian yearly

$TransmissionLiabilityCost\$:= TransLineLiability_{perkwperyr} \cdot PwrSt\_capacity$

$TransmissionLiabilityCost\$ = 1.5 \cdot 10^{6}$ $

Total annual costs of power station:

$$TotalAnnualCost\$:= FixedCost\$ + OperMaintenanceCost\$ + TransmissionLiabilityCost\$$$

$$TotalAnnualCost\$ = 12.15 \cdot 10^{6} \quad \$$$

Electrical Energy Generated Per year:

Hours per year: $HoursPerYear := 24 \cdot 365 = 8760$ Hours

$$ElectricalEnergyPerYear := PwrSt\_capacity \cdot HoursPerYear \cdot LF$$

$$ElectricalEnergyPerYear = 525.6 \cdot 10^{6} \quad \text{kWh}$$

Energy used in station for auxiliaries per year (2%)

$$EnergyUsedForAux := ElectricalEnergyPerYear \cdot Aux\_Energy$$

$$EnergyUsedForAux = 10.512 \cdot 10^{6} \quad \text{kWh}$$

Energy available at load centre per year:

$$EnergyAvailableLoadCntr := ElectricalEnergyPerYear - EnergyUsedForAux$$

$$EnergyAvailableLoadCntr = 515.088 \cdot 10^{6} \quad \text{kWh}$$

Cost of energy at load center:

This is equal to total annual cost divided by energy available at load center and the answer is given in cents per kWh instead of dollars per kWh.

$$ConvertToCents := 100$$

$$CostAtLoadCenter := \left(\frac{TotalAnnualCost\$}{EnergyAvailableLoadCntr}\right) \cdot ConvertToCents$$

$$CostAtLoadCenter = 2.359 \quad \text{cents per kWh}$$

In this problem transmission line loss was not given, when given then the net energy available for sale can be determined and the cost worked out. Sometimes for estimate of transmission line cost; percentage of capital cost at 12% is used. Refer to page 225.