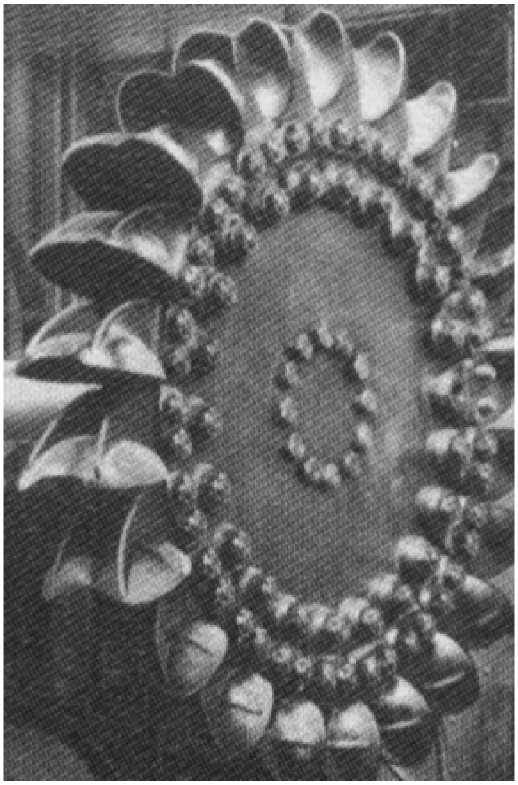
Hydropower

Hydropower systems convert hydraulic energy, the potential and kinetic energy of water, into mechanical or electrical work. Long employed by humans to provide useful work, hydraulic machines have evolved into high efficiency converters that provide electricity at relatively low costs compared to thermal converters, although the cost of hydroelectricity is intimately linked to the regional impacts associated with the intervention in the natural flow of surface waters. Atmospheric pollutant emissions are virtually nonexistent, except during construction, but there is by no means a universal consensus concerning the overall environmental benefits associated with hydrosystem development, regardless of facility scale. Most hydrosystems utilize a renewable source of energy, water lifted to elevation through evaporation and precipitation driven by solar energy. In the case of pumped storage hydrosystems, a non-renewable source of energy, such as fossil or nuclear electricity, may be employed to lift the water to elevation.

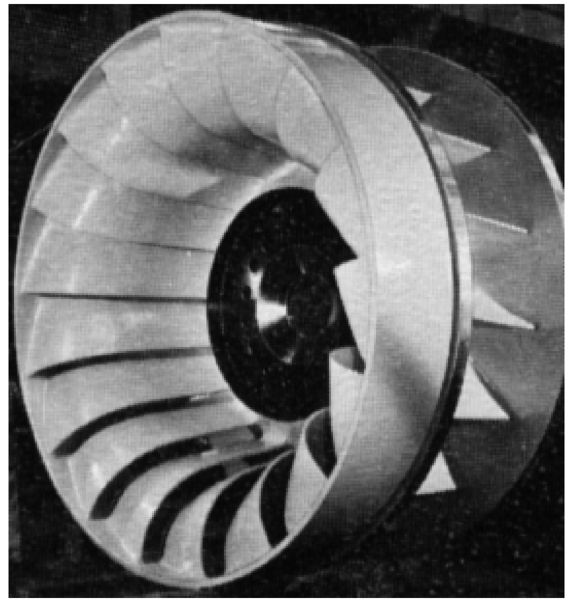


Impulse Turbine: Pelton

The power developed by a hydraulic machine, generally a hydraulic turbine, is related to the flow rate of water through the machine, and the potential and kinetic energy of the water source. Typically, an impoundment or reservoir is created to store the water for the facility, such that in the reservoir the velocity is low and kinetic energy is small in comparison to the potential energy represented by the height of the water above the turbine. Storage reservoirs are not, however, required for hydrosystem development, as noted below. Undershot water wheels were often placed in the stream flow without benefit of an upstream reservoir. Overshot wheels used both the kinetic energy of the flow and the potential energy represented by the water above the wheel. Hydrosystems are classified by size into four categories:

- Large hydrosystems greater than 30 MW capacity[1],
- Small hydrosystems less than 30 MW capacity,
- Mini-hydrosystems less than 1 MW capacity, and
- Micro-hydrosystems less than 100 kW capacity.

[1] The world's largest hydropower installation is currently Brazil's Itaipu facility with a capacity of 12.6 GW_e. China's Three Gorges project on the Yangtze river will total 18.2 GW_e when finished. The project will build in two phases, with phase 1 installing 14 Francis turbines of 700 MW_e each, and phase 2 with another 12 turbines.

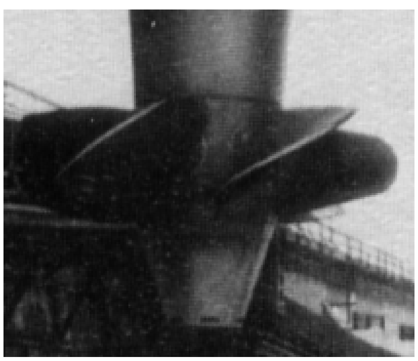


Reaction turbine wheel (on side): Francis

They are also classified according to the elevation difference, or head, between the water source and the turbine:

- High head installations with head greater than 150 m,
- Medium head installations with head between 20 and 150 m, and
- Low head installations with less than 20 m head.

A run-of-river plant draws water directly from the water course without an impoundment. The plant output is therefore dependent directly on the instantaneous flow rate of the stream, although the plant may not utilize all of the water available, especially under flood conditions. Variations in the height of water in the stream may have an influence on the available head for the facility, and may cause fluctuations in the facility output.



Reaction Turbine: Kaplan

A storage plant includes a dam and reservoir, and is generally not subject to the same types of variation as the run-of-river type. The construction of a dam and impoundment adds to the cost of the facility, may have undesirable environmental consequences due to flooding behind the dam, but may also provide for downstream flood control, and improved agricultural, industrial, and municipal water supplies. Engineering guidelines for the evaluation of the safety of dams and reservoirs for hydrosystem projects have been developed[2].

Pumped storage facilities are storage plants which have an associated source of energy, such as a nuclear, fossil, or wind plant that can be used to pump water back into the reservoir after it has been released through the turbines. The two operations are separated in time. Pumped storage is often employed for the purposes of increasing the available peaking capacity of a utility electric system (e.g. during the day when heavy air conditioning load exists). During off-peak periods (e.g. at night) when low cost baseload electrical energy may be available in surplus, water is pumped uphill into the reservoir in preparation for the next peak demand period. In this way, the average cost of power can be reduced.

[2]FERC. 1991. Engineering guidelines for the evaluation of hydropower projects.

Virtually all modern hydrosystems utilize hydraulic turbines as the primary energy converter. Turbines are classified into two types depending on how the water does work on the runner, or the moving part of the machine:

- Impulse turbines, such as the Pelton, Turgo, and crossflow types, which utilize the kinetic energy in a high velocity stream, or jet, of water, and

- Reaction turbines, such as the Francis, Kaplan, and propeller types, which utilize both pressure (potential) and kinetic energy.

Reaction turbines are submerged in the water flow, impulse turbines are generally not (Figures 1a-c).

Basic power equation for hydrosystems:

A schematic arrangement for a storage plant is shown in Figure 2. Water in the impoundment has a surface elevation z_1 (m) above some datum. The centerline of the turbine is at an elevation z_2, and the tail water (discharge water) surface level is at z_3. A duct called a penstock connects the water in the reservoir or water source to the turbine housing. Gates (not shown) are used to control the flow rate of water through the turbine to vary the power output. The turbine is connected to a generator for the purposes of generating electricity. The power output of the turbine is found from a first law analysis of the system. Between points 1 and 3,

$$z_1 + \frac{V_1^2}{2g} + \frac{p_1}{\gamma} = z_3 + \frac{V_3^2}{2g} + \frac{p_3}{\gamma} + h + h_f \qquad [1]$$

where z_i are the elevations (m)
V_i are the velocities of the flow (m s^{-1})
p_i are the fluid static pressures (Pa)
h is the net head utilized by the turbine (m)
h_f is the friction head loss between reservoir and turbine (m)
g is the acceleration of gravity (m s^{-2})
and $\gamma = \rho g$ is the specific weight of water (N m^{-3})
with ρ = density of water (kg m^{-3})

If the reservoir is large such that the velocity, V_1, is low, it may be neglected in equation [1] without substantial error (it actually cannot be zero otherwise there would be no work production). Also, with $p_1 = p_3$, h may be solved for as

$$h = z_1 - z_3 - \frac{V_3^2}{2g} - h_f \qquad [2]$$

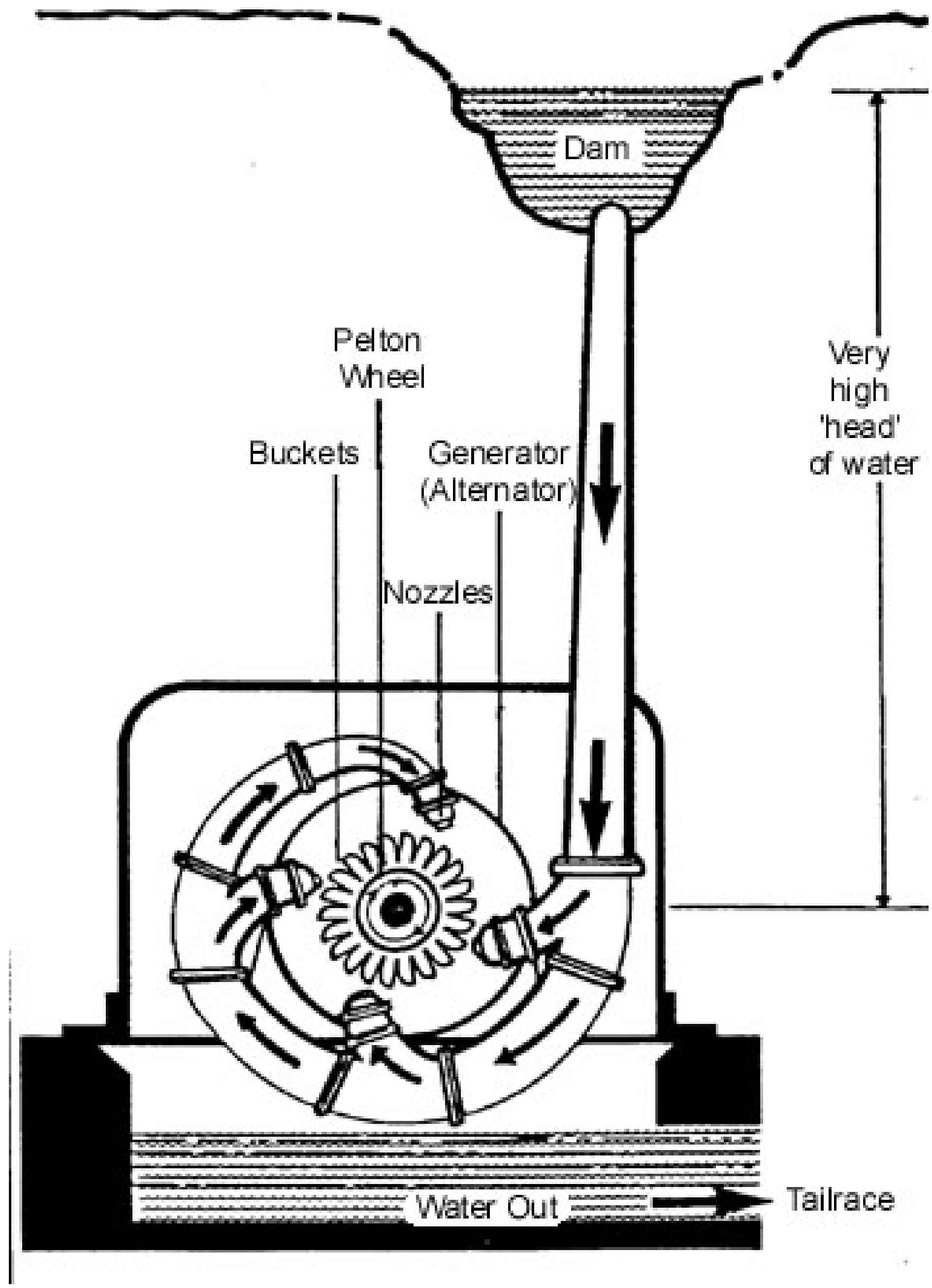


Figure 1a. Pelton wheel installation.
(source: http://www.acre.murdoch.edu.au/ago/hydro/hydro.html)

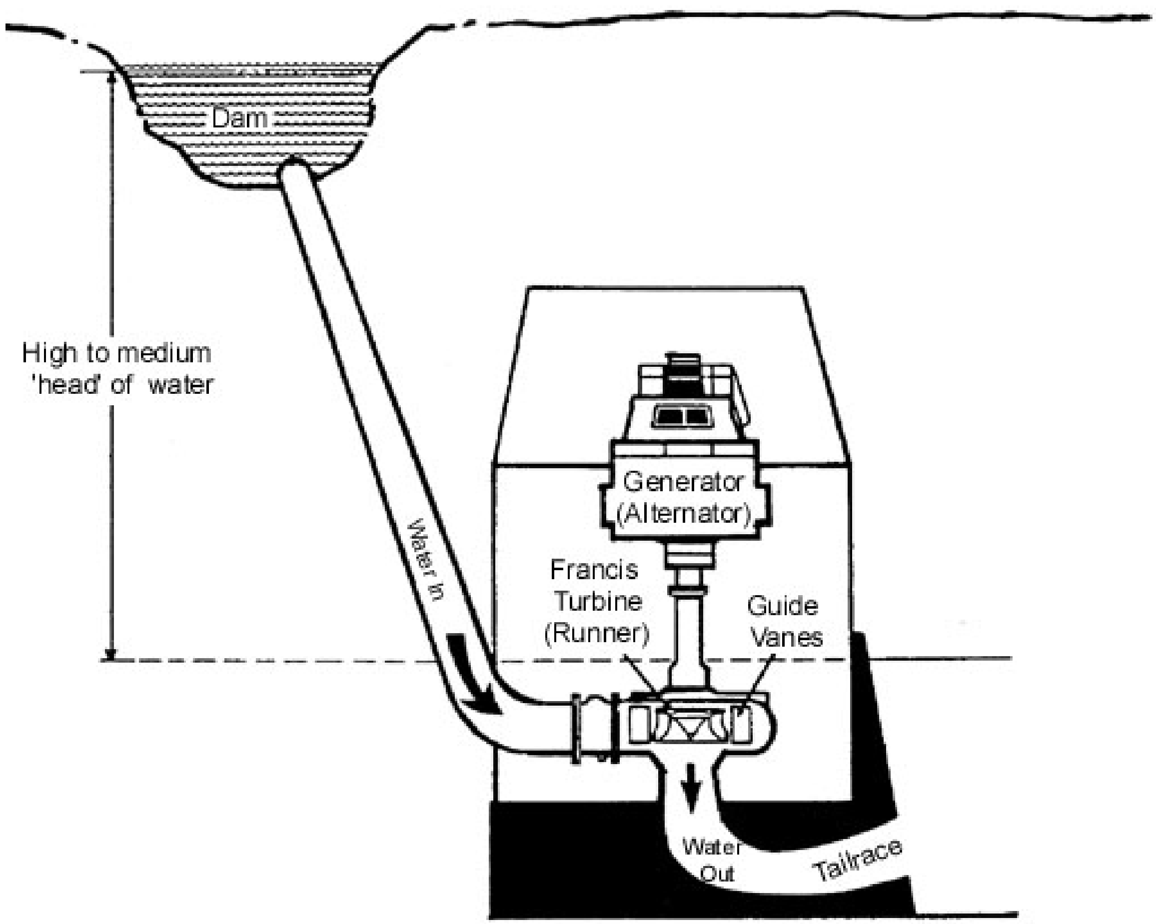


Figure 1b. Francis turbine installation.
(source: http://www.acre.murdoch.edu.au/ago/hydro/hydro.html)

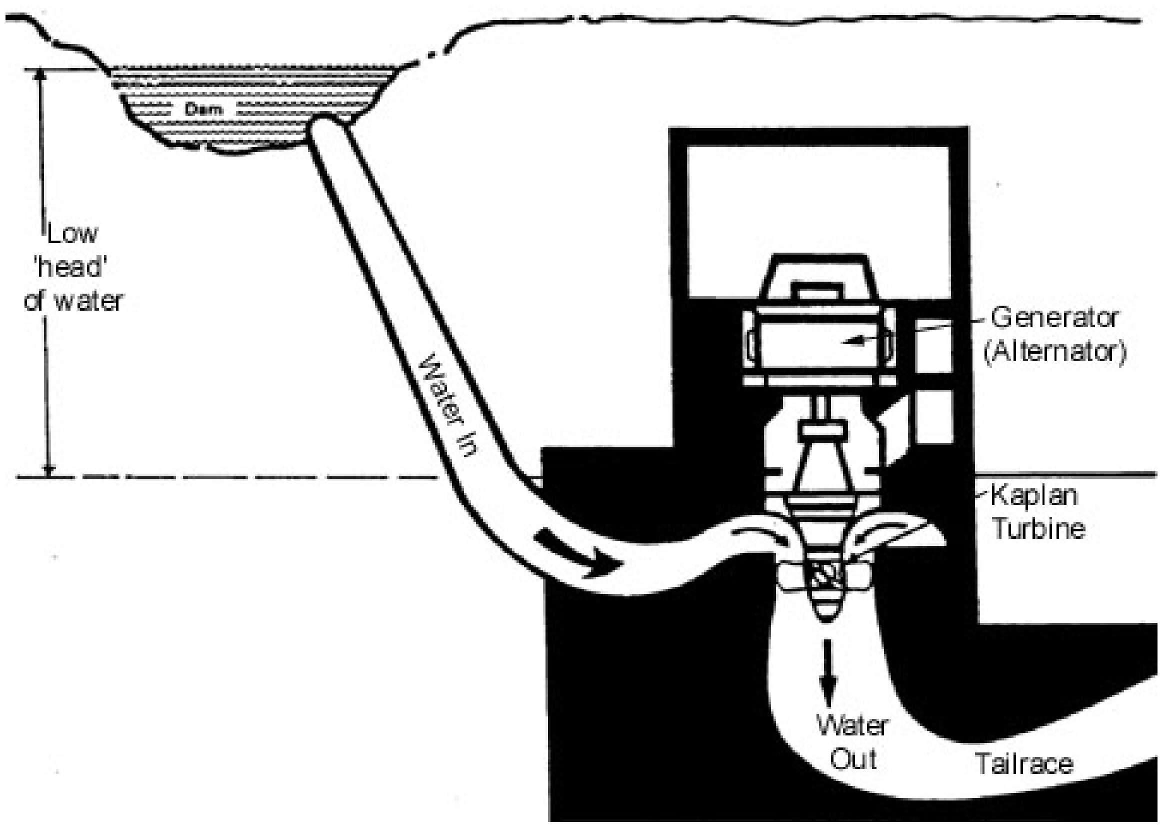


Figure 1c. Kaplan or propeller turbine installation.
(source: http://www.acre.murdoch.edu.au/ago/hydro/hydro.html)

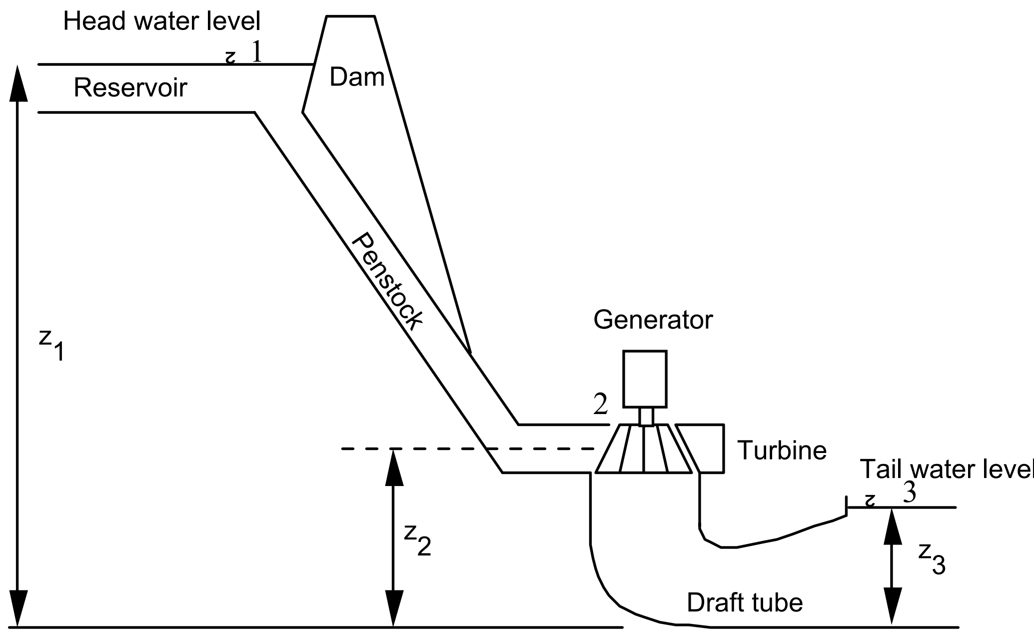


Figure 2. Schematic hydroelectric power plant.

The power extracted from the flow, $\dot{W}$, is

$$\dot{W} = \dot{m}gh \tag{3}$$

where $\dot{m}$ = mass flow rate of water (kg s^{-1})

From continuity,

$$\dot{m} = \rho AV = \rho Q \tag{4}$$

Q = flow rate of water (m^3 s^{-1}).

Then,

$$\dot{W} = \rho Qgh = \gamma Qh \tag{5}$$

Taking into account the turbine efficiency, η, the actual power output of the system is

$$\dot{W} = \eta\gamma Qh \tag{6}$$

Engineering surveys are required to gage the stream flows and heads available for a planned hydrosystem. For small systems, where a quick estimate of the potential power development is needed as a means to decide whether further surveys should be conducted, the head is often readily measured, but the flow may not be due to the irregular profile of the stream bed. A weir may be placed across the flow temporarily to gage the flow rate. Alternatively, the depth of the stream may be measured in several places across it to obtain a rough cross-sectional profile. If a stick or other floating object is thrown into the stream near the middle, and timed as it travels some measured distance downstream, an average stream velocity can be found as roughly 70% of the surface (stick) velocity (assumes quasi-laminar flow). The stream cross-section can be integrated to obtain a rough measure of the area of the flow, which when combined with the estimate of velocity yields an estimate of the flow rate. For siting purposes, the height of flood should also be determined so as to site critical equipment above the maximum water level. If no records exist, a survey of the region may reveal branches and other debris left in trees from a flood, indicating the height to exceed. This should also suggest the maximum head available.

Selection example:

Consider a run of the river installation with the stream flow and net head characteristics listed in Table 1. The first column entitled "percent exceedance" is the fraction of time during a year that the flow exceeds the value shown in the second column, "river flow." The first row indicates that the flow in the river has never exceeded 368 m^3 s^{-1}. Ten percent of the time the flow exceeds 86 m^3 s^{-1}. Such stream flow data should be as representative as possible of the average flows, and is often taken as an average over 30 years or for as long as records exist. Forecasting stream flows should take account of the stochastic nature of the regional precipitation and watershed characteristics, as well as any human intervention that may have caused changes to occur in the flow.

Table 1. Stream flow characteristics for hydrosystem example.

Percent exceedance	River flow (m3 s-1)	Net head (m)	Turbine discharge (m3 s-1)	Efficiency (%)	Power (MW)	Energy (MWh)
0	368.0	9.5	50.0	87	4.05	
10	86.0	9.8	50.0	87	4.18	3,604
20	50.0	10.0	50.0	87	4.26	3,697
30	26.2	10.0	26.2	92	2.36	2,902
40	20.6	10.0	20.6	92	1.86	1,848
50	15.0	10.0	15.0	89	1.31	1,387
60	13.8	10.0	13.8	87	1.18	1,088
70	12.6	10.0	12.6	85	1.05	975
80	11.0	10.0	11.0	83	0.89	852
90	9.0	9.5	9.0	78	0.65	678
100	4.0	9.0	4.0	54	0.19	370
Total Annual						17,400

The third column in Table 1 gives the net head available to the turbine. The net head is determined on an iterative basis from the size of the turbine, as turbine flow can influence the head. Note that in the table, the head is lower for high stream flows than at intermediate values. This may occur under flood when the tail water elevation rises above its design level faster than the head water elevation (which may be controlled by a dam in a storage plant). At very low flows, the head may also decrease due to the decline in head water elevation, with tail water maintained at the same level. Each site and installation will have its own characteristics.

The fourth column in the table gives the turbine discharge. The turbine is shown to be rated for a 50 m^3 s^{-1} discharge rate. The selection of this rate should nominally come from a cost optimization study on the site, unless other factors take precedence. The annual energy generation and cost of power are sensitive to the selection of the turbine discharge capacity. For a run of river plant, when the stream flow exceeds the plant rated flow, the excess water simply bypasses the plant. When the stream flow is less than the rated flow, all water is assumed to flow through the plant. The stream flow and turbine discharge are illustrated in Figure 3.

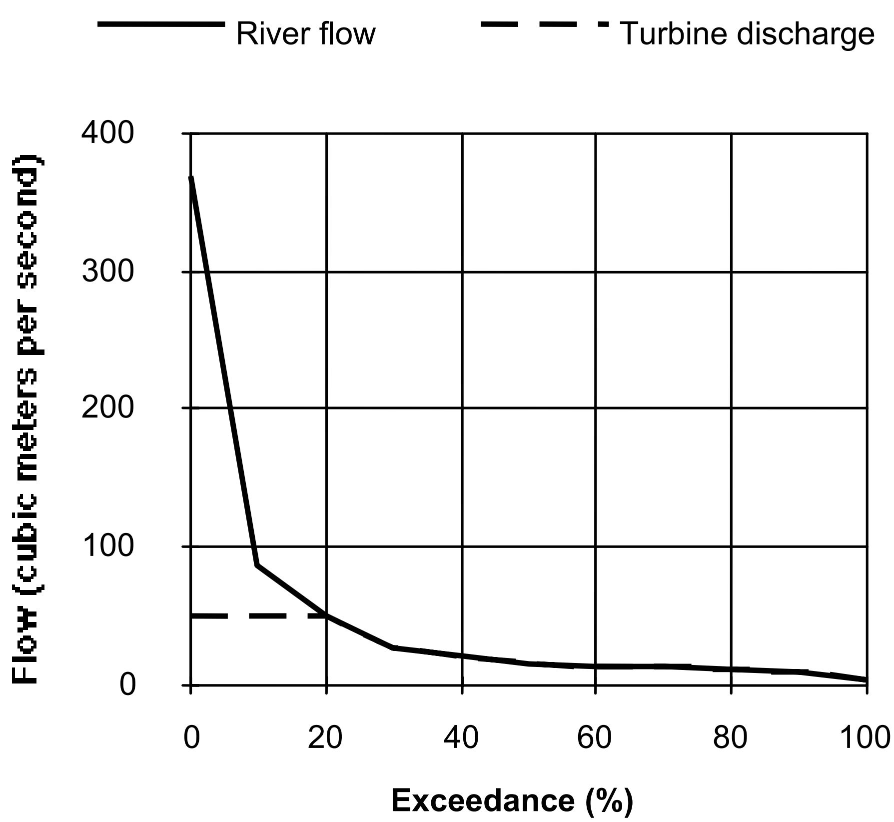


Figure 3. Stream flow duration and turbine discharge for the selection example.

The efficiency of the plant shown in the fifth column of the table depends on the rated size of the turbine and the fraction of rated flow available to it. Figure 4 illustrates the change in turbine efficiency for various hydraulic machines as a function of the percent of rated power[3]. The so-called turn-down capacity of hydraulic turbines tends to be quite good, as the efficiency remains high over a large fraction of the operating range. At high turn-down (low percent of rated power), the efficiency drops rather precipitously, however.

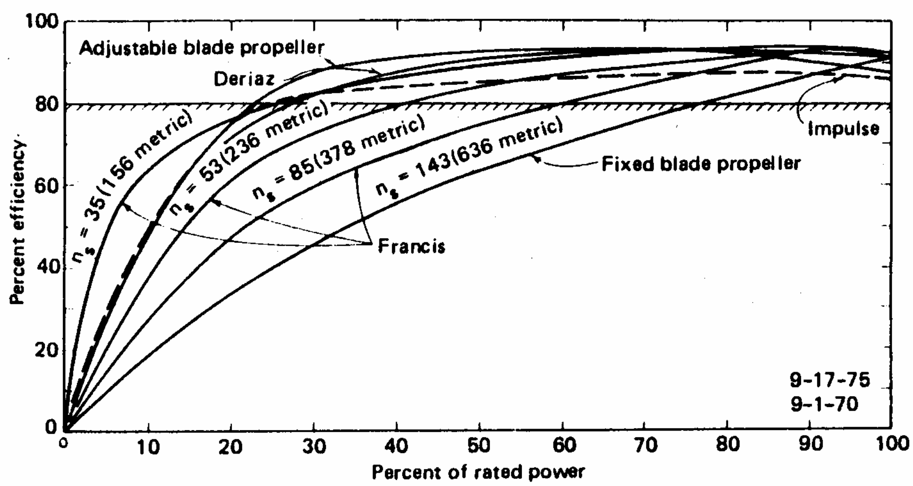


Figure 4. Hydraulic turbine efficiency[2].

The rated capacity, $\dot{W}_R$, of the turbine is found from equation [6] for the head and flow rate selected, with the appropriate turbine efficiency.

$$\dot{W}_R = (0.87)(9{,}800 \text{ N m}^{-3})(50 \text{ m}^3 \text{ s}^{-1})(10 \text{ m}) = 4{,}263{,}000 \text{ W}$$

or 4.26 MW. This system is classified as a small hydrosystem. By choosing different rated turbine discharge flows, and computing the cost of energy from the plant at that size, the optimal plant capacity can be found. Quite typically an optimum size will lie in the region of the knee of the stream flow duration curve shown in Figure 3.

The annual energy production by the turbine can be found by integrating the power over the flow duration. The result is shown in the last column of Table 1. Each value represents the energy generated over the flow duration interval. The sum over all intervals is the annual energy generation. The values listed were computed by taking the average power over the interval, and multiplying by the time in the interval. For

[3]Warnick, C.C. 1984. Hydropower engineering. Prentice Hall, New Jersey.

example, between 0 and 10% exceedance, the average power is (4.05 + 4.18 MW)/2, or 4.12 MW. The time in the interval is (0.1)(8,760 h y^{-1}), or 876 h. The generation in the interval is then about 3600 MWh. This assumes that the plant operates continuously. If the plant operates intermittently, then the time in the interval and the flowrate must be adjusted. The annual generation is increased for this example if the size of the turbine is increased. However, the annual energy generation does not increase in direct proportion to the turbine size because of the limited duration at high stream flow. Selecting a turbine for the largest flow at 0% exceedance, which gives a much larger turbine capacity, increases the annual generation by a relatively small amount. In addition to the limited duration at high flows, the turbine operates at high turn-down most of the time, which reduces the turbine efficiency and the energy generation in the low flow intervals. The cost of energy may increase compared to a smaller turbine because of the higher capital cost of the plant without proportional increases in energy generation and revenue.

The type of turbine to be used depends on both the capacity and head. Different turbine types are preferred for different combinations of these two parameters. A selection guide is given in Figure 5.

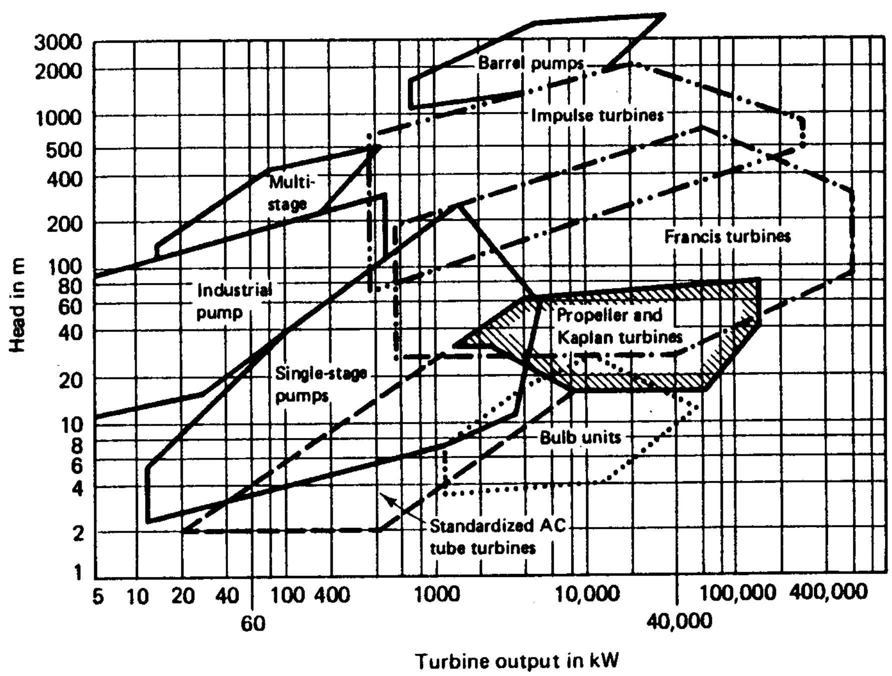


Figure 5. Turbine selection guide[2].

For the example considered here with 4 MW capacity and 10 m head, Figure 5 suggests a bulb type or tubular type turbine is preferred. From that information a number of other parameters can be determined which are useful in specifying the plant design. For example, the rotational speed of the turbine may be found from correlations on the so-called specific speed, N_s, of the turbine, defined as

$$N_s = \frac{N\dot{W}^{1/2}}{h^{5/4}} \qquad [7]$$

with N the turbine speed in rpm at the best turbine efficiency. For equation [7] $\dot{W}$ is in kW.

Figure 6 shows some of the correlations developed for various turbine types. In the case of a tubular type unit employing a propeller turbine,

$$N_s = \frac{1107.3}{h^{0.2998}} \qquad [8]$$

which for a 10 m head yields a specific speed of 555. The turbine speed is then

$$N = \frac{N_s h^{5/4}}{\dot{W}^{1/2}} = \frac{(555)(10)^{5/4}}{\left(4.26x10^3\right)^{1/2}} = 150\,\text{rpm}$$

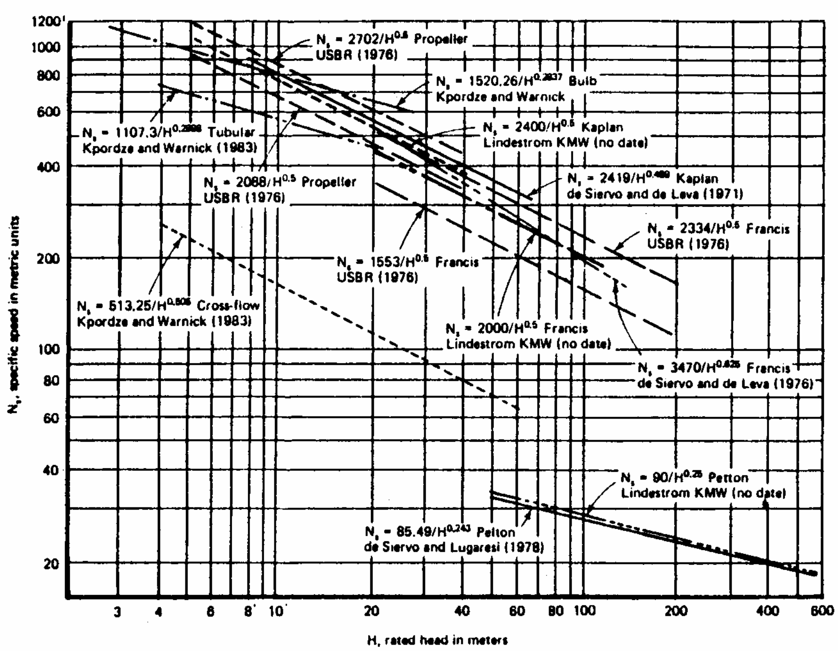


Figure 6. Specific speed correlations for various turbine types[2].

An estimate of the turbine diameter, D (m) can be found from another correlation[2] for propellers,

$$D = (66.76 + 0.136 N_s)\frac{\sqrt{h}}{N} \qquad [9]$$

which yields a diameter of 3 m for the example here. The generator design can also be specified. The rotational speed, n, of an AC generator with a number of poles, p, to produce a frequency, f (Hz), is

$$n = \frac{120 f}{p} \qquad [10]$$

For a direct connected generator running at the same speed as the turbine in the example and generating at 60 Hz (US, Europe 50 Hz), the generator would need 48 poles. Alternatively, a gearbox could be used to increase the speed of the generator and reduce the required number of poles[4].

Another design consideration involves the setting of the turbine with respect to the tail water. Situating the turbine above the tail water elevation is preferred as it reduces the amount of excavation and construction costs. The draft tube is provided with reaction turbines to recover the velocity head of the flow, so that situating the turbine somewhat higher does not constitute a significant loss in net head (see Figures 1b, c and 2). The flow area of the draft tube increases towards the outlet, and the velocity declines as the flow moves away from the turbine. The result is an increase in the net head, as may be seen from equation [2]. However, the turbine must not be set so high that the suction developed at the turbine from the flow through the draft tube results in cavitation at the turbine. Cavitation can cause severe damage to the turbine runner. The cavitation coefficient, known as Thoma's sigma, σ, is defined in terms of the water pressure (or head), and the atmospheric and vapor pressure heads,

$$\sigma = \frac{h_a - h_v - h_s}{h} \qquad [11]$$

where h_a = absolute atmospheric pressure head = p_{atm}/γ (m)
h_v = vapor pressure head (m)
h_s = suction head (m) = (elevation at turbine discharge) - (minimum tail water elevation)
h = net head (m)

[4]Monition, L., M. Le Nir and J. Roux. 1984. Micro hydroelectric power stations. John Wiley and Sons, New York.

The critical cavitation coefficient, σ_{cr}, is defined as the maximum σ above which cavitation is likely. The maximum suction head, and thus the turbine setting, can be found as

$$h_s = h_a - h_v - \sigma_{cr} h \qquad [12]$$

The critical cavitation coefficient has been correlated to the specific turbine speed as

$$\sigma_{cr} = \frac{N_s^{1.64}}{50{,}227} \qquad [13]$$

For the example, with N_s = 555, σ_{cr} = 0.63. For a sea level setting, if the water temperature is 15°C, the vapor pressure of water is 1,762 Pa, and the critical suction head is found as

$$h_a = \frac{101{,}325 \text{ Pa}}{9{,}800 \text{ N m}^{-3}} = 10.3 \text{ m}$$

$$h_v = \frac{1{,}762 \text{ Pa}}{9{,}800 \text{ N m}^{-3}} = 0.2 \text{ m}$$

h_s = 10.3 - 0.2 - 0.63(10) = 3.8 m

In this example, the turbine should not be set more than 3.8 m above the minimum tail water level to avoid cavitation at the runner. The critical suction head declines with increased elevation due to the reduction in h_a with height. The value of h_a decreases about 1.1 m for every 1,000 m increase in elevation[5]. For plants situated at high elevation, the critical suction head may be negative, and the turbine outlet may need to be set below the tail water level to avoid cavitation.

Cost of energy:

Hydrosystems tend to have a larger share of fixed costs than operating costs compared to thermal station power plants. Costs for operation and maintenance may typically run about 2% of the annual capital cost charge. Hydrosystems also tend to be subject to economies of scale, both in terms of capital cost and operation. However, they are increasingly difficult to site due to the limited number of locations with good head and flow, and the potentially adverse environmental impacts where impoundments or significant intervention in stream flow are required.

As mentioned above, under certain circumstances the plant size may be optimized. Consider a run-of-river plant as in the previous example. Using the data of Table 1, and

---

[5]Gulliver, J.S. and R.E.A. Arndt. 1991. Hydropower enegineering handbook. McGraw-Hill, New York.

information concerning capital and operating costs of various size facilities, an economic analysis could be carried out to locate the rated turbine capacity giving the lowest cost of energy. The optimization can be performed numerically, using tabulated data, or analytically if appropriate correlations can be developed for the stream flow duration, turbine efficiency, and net head. As an example, a stream flow duration curve as in Figure 3 might be modeled by a correlation of the form

$$Q = at^{b} \qquad [14]$$

where a, b = constant coefficients
t = exceedance time, or the time in hours per year the flow exceeds the value Q

An approximate model of the turbine efficiency (which fails to model the small drop-off in efficiency for operation near the rated capacity) can be written as

$$\eta = \left(\frac{Q}{Q_R}\right)^{f} \qquad [15]$$

Q_R = rated flow for the turbine at its rated capacity
f = constant coefficient

Assuming the plant to be a baseload facility, that is, operated continuously, an inspection of Figure 2 shows the annual energy generation to be,

$$E = \dot{W}_R t_R + \int_{t_R}^{8,760} \dot{W} dt \qquad [16]$$

t_R = rated exceedance time (exceedance value in hours giving the rated turbine flow, Q_R

The first term on the right accounts for the energy generation when the stream flow exceeds or is equal to the rated turbine flow. The second term accounts for the energy generation when the stream flow is less than the rated turbine flow.

If the capital costs (and operating costs as well) are subject to an economy of scale, the cost of the facility may be obtained from

$$C = m\dot{W}_R^{s} \qquad [17]$$

m = constant coefficient
s = scale factor (--)

The cost of energy, *COE* (\$ Wh^{-1}), based on capital cost alone, can then be found to be

$$COE = \frac{C(A/P)}{E} = \frac{m\left(\xi_1 t_R^b\right)^s (A/P)}{(\xi_1 - \xi_2)t_R^{b+1} + \xi_3 t_R^{-bf}} \qquad [18]$$

$$\xi_1 = \eta_R \gamma h a$$

$$\xi_2 = \frac{\xi_1}{b(1+f)+1}$$

$$\xi_3 = \frac{\xi_1 (8{,}760)^{b(1+f)+1}}{b(1+f)+1}$$

(A/P) = capital recovery factor

Note that equation [18] assumes constant head over all flows. Taking

$$\frac{dCOE}{dt_R} = 0$$

to solve the objective function *minimize COE*, the optimum value of t_R is

$$t_R = 8760\left[\frac{(s+f)}{(1+f)(b+1-bs)}\right]^{\frac{1}{bf+1+b}} \qquad [19]$$

in which the optimum t_R depends only on the values of the exponents *b*, *f*, and *s*. Where the facility is neither run-of-river nor base-loaded, the results [18] and [19] would not apply. This example is included here simply for the purposes of indicating that with an economy of scale in the facility cost, an optimum capacity may exist. Note that in the case of $s = 1$, equation [19] yields t_R = 8,760 h, which says simply that with no economy of scale, the lowest cost is achieved by rating the plant at the lowest flow, thereby achieving the lowest expenditure of capital. This may not meet the design criteria, of course. The ability to optimize in the manner of equation [19] assumes a rather free choice in the amount of power generated, when other factors may dictate the size of plant.