Small Hydro Project Analysis

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SMALL HYDRO PROJECT ANALYSIS

This course covers the analysis of potential small hydro projects including a technology background.

Small Hydro Background

Hydroelectricity is a widely used form of alternative energy, providing more than 19% of the world's electric power consumption from both large and small hydro power plants. Brazil, the United States, Canada and Norway generate large quantities of electric power from very large hydroelectric facilities. On the other hand, there are numerous regions of the world that have a huge number of small hydro power plants in service. For example, in China, more than 19,000 MW of electric power is generated from 43,000 small hydro power plants.

There is no common definition of the term "small hydro power plant" which, depending on local interpretations can range from a few kilowatts to 50 megawatts or more of electric power output. Internationally, "small" hydro power plants usually range in size from 1 MW to 50 MW. Projects in the 100 kW to 1 MW range are usually referred to as "mini" hydro plants, and projects under 100 kW in size are referred to as "micro" hydro power plants. However, installed capacity is not always a proper indicator of the project size. For instance, a 20 MW, low-head "small" hydro power plant is not small since low-head hydro facilities usually need and use larger volumes of water, and need larger hydro turbines in comparison to high-head facilities.

Description of Small Hydro Power Plants

A small hydro power plant can be defined under two main sections: civil works, and electrical and mechanical equipment.

Civil works

The major civil works of a small hydro power plant construction are the diversion dam or weir, the water passages and the powerhouse for electrical and mechanical equipment. The diversion dam or weir directs the water into a canal, tunnel, penstock or turbine inlet. The water then goes through the turbine, spins it with sufficient force to generate electric power in a generator. The water then goes back into the river through a tailrace. In general, small hydro developments built for use at isolated and remote areas are run-of-river facilities, which mean that water is not kept in a reservoir and is utilized only as it is available. The price of huge water storage dams cannot usually be justified for small hydro power plant developments and finally, a low dam or diversion weir of the simplest construction is usually applied. Dam construction can be of concrete, wood, masonry or a combination of these materials. Significant effort continues to be put to decrease the price of dams and weirs for small hydro developments, as the price of this item alone usually renders a project not economically viable.

The water passages of a small hydro power plant consist of:

- An intake that includes trashracks, a gate and an entrance to a canal, penstock or directly to the turbine which depends on the facility type. The intake is normally constructed of reinforced concrete, the trashrack of steel or iron, and the gate of wood, iron or steel.

- A canal, tunnel and/or penstock, that transfers the water to the powerhouse in facilities where the electric and mechanical powerhouse is located at a distance downstream from the intake. Canals are usually excavated and follow the contours of the existing terrain. Tunnels are underground and made by drilling and blasting or by using a tunnel-boring equipment. Penstocks, that convey water under pressure, can be constructed of steel, iron, fibreglass, plastics, concrete or wood.

- The entrance and exit of the mechanical turbine that include the valves and gates required to shut off flow to the turbine for shutdown and maintenance purposes. These elements are usually made of steel or iron. Gates downstream of the turbine, if needed for maintenance, can be constructed of wood.

- A tailrace that transfers the water from the turbine exit back to the river. The tailrace is excavated just like the canal. The turbine or turbines and most of the electrical and mechanical components are located at the powerhouse. Small hydro power plants are usually kept to the minimum possible size while still providing sufficient foundation strength, access for servicing, and safety. Construction is made of concrete and other local building materials and components.

Design simplicity, with an emphasis on usability, easily made civil structures is of major concern for a small hydro power plant project in order to keep prices at a minimum.

Electrical and mechanical equipment

The major mechanical and electrical elements of a small hydro power plant are the turbine(s) and electrical generator(s). Several different turbines types have been made to cover the vast range of hydropower site conditions that can be found around the world. Mechanical turbines that are used for small hydro power developments are scaled-down versions of conventional large hydro power turbines. Mechanical turbines that are used for low to medium head developments are typically of the reaction type and include Francis and fixed and variable pitch (Kaplan) propeller mechanical turbines. The turbine runner or “wheel” of a reaction turbine is totally submersed in water. Mechanical turbines utilized for high-head developments are usually referred to as impulse turbines. These turbines include the Pelton, Turgo and crossflow arrangements. The impulse turbine runner rotates in the air and is powered by a high-speed water jet.

Small hydro power turbines can reach efficiencies of around 90%. Care must be taken when selecting the suitable turbine design for each development as some mechanical turbines only effectively service over a limited flow range (e.g. propeller mechanical turbines with fixed blades and Francis mechanical turbines). For many run-of-river small hydro power sites where water flows significantly change, turbines that function efficiently over a wide flow range are typically preferred (e.g. Kaplan, Pelton, Turgo and crossflow designs).

Instead, multiple turbines that work within limited water flow ranges can be utilized. There are two basic electrical generator types used in small hydro power plants:

induction (asynchronous) or synchronous. A synchronous electrical generator can function in isolation while an induction generator must typically function in conjunction with other electrical generators. Synchronous generators are utilized as the primary power source by electrical utility companies and for isolated diesel-grid and stand-alone small hydro power developments. Induction electrical generators with capacities less than about 500 kW are normally best fitted for small hydro power plants delivering power to a large existing electricity network.

Other electrical and mechanical elements of a small hydro power plant include:

- Speed increaser to match the rotational speed of the mechanical turbine to that of the electrical generator (if needed)
- Water shut-off valve(s) for the mechanical turbine(s)
- River by-pass gate and checks (if needed)
- Hydraulic control mechanism for the mechanical turbine(s) and valve(s)
- Electrical relay protection and control system
- Electrical switchgear
- Power transformers for station service and electricity transmission
- Station service that includes lighting, heating and power to operate control systems and electrical switchgear
- Water cooling and lubricating mechanisms (if needed)
- Ventilation mechanisms
- Backup power supply
- Telecommunication mechanism

- Fire and security alarm mechanism (if needed)

- Utility interconnection or transmission and distribution electrical system

Small Hydro Power Project Development

The small hydro power project development usually needs from 2 to 5 years to finish, from conception to final commissioning. This time is needed to complete studies and engineering design work, to receive the necessary legal approvals and to construct the project. Once the small hydro power plant is constructed, it requires insignificant maintenance over their useful life cycle, which can be more than 50 years. Typically, one part-time operator can perform control and routine service of a small hydro plant, with maintenance of the larger and more important elements of a plant normally needing assistance from outside contractors.

The technical and financial feasibility of each small hydro power development are very site dependant. Power and energy production depends on the available water (flow) and head (drop in elevation). Power and energy amount that can be produced depends on the water quantity and the frequency of flow during the year.

The site economics depends on the energy and power that a development can generate, whether or not the power can be sold, and the cost paid for the power. In an isolated area (off-grid and isolated-grid developments) the value of energy produced for consumption is typically significantly higher than for developments that are interconnected to a central-grid. However, isolated areas may not be in a position to use all the available power from the small hydro power plant and, maybe not in a position to use the power when it is available due to seasonal fluctuations in water flow and energy usage.

A typical, “rule-of-thumb” relationship is that hydro project power is equal to seven times the product of the flow (Q) and gross head (H) at the site ($P = 7QH$). In order to generate 1 kW of power at a location with 100 m of head, this will need one-tenth the water flow that a location with 10 m of head would need. The hydro turbine size is dependent on the water flow it has to accommodate. Thus, the power producing equipment for higher-head, lower-flow developments is usually less expensive than for lower-head, higher-flow small hydro power plants.

The same cannot be confirmed for the civil works elements of a small hydro power project that are related much more to the local topography and physical nature of a particular location.

Small hydro development types

Small hydro developments can usually be categorised as either “run-of-river developments” or “water storage developments”.

Run-of-river development type

“Run-of-river” refers to an operation mode in which the hydro power plant uses only the water that is available in the river natural flow. “Run-of-river” means that there is no water storage and that power varies with the stream flow.

The power and energy production of run-of-river small hydro power plants changes with the hydrologic cycle, so they are usually best fitted to provide power to a bigger electricity system. They do not typically deliver much firm capacity. Therefore, isolated locations that use small hydro resources usually need auxiliary power. A run-of-river power plant can only meet all of the electrical requirements of an isolated location or industry if the minimum water flow in the river is adequate to meet the load’s peak power needs.

Run-of-river small hydro power plant can call for diversion of the river water flow. Diversion is usually needed to take advantage of the drop in elevation that occurs over a distance in the river. Diversion developments decrease the flow in the river between the intake and the powerhouse. A diversion weir or small dam is usually needed to divert the flow into the intake.

Water storage (reservoir) developments

For a hydroelectric plant to generate power on demand, either to meet a changing load or to meet peak power, water must be kept in one or more reservoirs. Unless a natural lake can be tapped, providing storage typically needs the development of a dam or dams and the creation of new lakes. This affects the local environment in both negative and positive directions, even though the scale of project usually amplifies the negative effects. This usually delivers a conflict, as greater hydro power developments are appealing since they can deliver “stored” power during peak demand periods. Due to the economies of scale and the complex approval procedure, storage systems tend to be relatively big in size.

The development of new storage reservoirs for small hydro power plants is usually not economically viable except, at remote sites where the energy price is very high. Storage at a small hydro power plant, if any, is usually limited to small volumes of water in a new head pond or existing lake upstream of an existing dam. Pondage is the term applied to define small quantities of water storage. Pondage can offer advantages to small hydro power plants in the form of increased power generation and/or enhanced income. Another type of water storage project is “pumped storage” where water is “recycled” between downstream and upstream storage reservoirs. Water is directed through mechanical turbines to produce power during peak periods and pumped back to the upper reservoir during off-peak periods. The feasibility of pumped storage developments depends on the difference between the values of peak and off-peak power. Due to the inefficiencies involved in pumping versus producing, the water recycling leads in net energy consumption. Power used to pump water has to be produced by other sources.

The environmental effects that can be connected with small hydro power projects can change significantly depending on the project location and site configuration.

The implications on the environment of constructing a run-of-river small hydro power plant at an existing dam are usually minor and similar to those related to the expansion of an existing development. Construction of a run-of-river small hydro power plant at an undeveloped location can pose extra environmental effects. A small dam or diversion weir is typically needed. The most feasible project scheme might involve flooding some rapids upstream of the new small dam or weir.

The environmental effects that can be linked with hydroelectric projects that contain water storage (typically larger in size) are primarily linked to the creation of a water storage reservoir. The creation of a reservoir calls for the development of a relatively big dam, or the use of an existing lake to impound water. The creation of a new reservoir with a dam involves the flooding of land upstream of the dam. The utilization of water stored in the reservoir behind a dam or in a lake ends in the changing of water levels and flows in the river downstream. A rigorous environmental judgement is usually needed for any development involving water storage.

Hydro project engineering steps

There are usually four steps for engineering work needed to construct a hydro development. Note, however, that for small hydro power plant, the engineering work is usually reduced to three steps in order to reduce costs. Typically, initial investigation is contracted that mixes the necessary work in the first two steps presented below.

The work, however, is finished to a reduced level of detail in order to reduce costs. While decreasing the engineering work enhances the danger of the development not being financially feasible, this can normally be justified due to the lower prices linked with smaller developments.

Reconnaissance surveys and hydraulic assessments

This first step of work usually covers various sites and includes: map assessments; delineation of the drainage basins; initial approximations of flow and floods; a one day site visit to each site (by a design engineer and geologist or geotechnical engineer); initial layout; final grading of locations based on power potential; cost approximations (based on equations or computer data) and an index of prices.

Pre-feasibility assessment

Development on the selected locations or sites would involve: site mapping and geological assessments (with drilling confined to locations where foundation uncertainty would have a critical impact on prices); a reconnaissance for adequate borrow locations (e.g. for sand and gravel); an initial layout based on materials known to be available; initial selection of the main development features (installed capacity, type of construction, etc.); a price assessment based on major amounts; the identification of potential environmental effects; and production of a single volume assessment report on each location.

Feasibility assessment

Development would go forward on the selected locations with a major foundation investigation exercise; delineation and testing of all borrow locations; assessment of diversion, design and potential maximum floods; determination of energy generating potential for various dam heights and installed capacities for development optimisation; determination of the development design earthquake and the maximum possible earthquake; design of all civil structures in adequate detail to get amounts for all items that contribute more than about 10% to the price of individual developments; determination of the dewatering sequence and development plan; optimization of the development layout, water levels and elements; production of a detailed price approximation; and eventually, an economic and financial assessment of the development including an evaluation of the effect on the existing power network along with a comprehensive assessment study.

System planning and project engineering

This task would involve assessments and final design of the electrical transmission network; integration of the transmission network; integration of the development into the electricity grid to check precise servicing mode; preparation of tender drawings and equipment specifications; assessment of bids and detailed design of the development; preparation of detailed development drawings and review of manufacturer’s equipment drawings. However, the limits of this phase would not involve site supervision nor development management, since this task would form part of the development execution prices.

Small Hydro Project Modelling

Small hydro power project modelling gives a means to evaluate the available power at a potential small hydro location that could be delivered to a central-electricity grid or, for isolated loads, the part of this usable power that could be harnessed by a local power company (or utilized by the load in an off-grid network). Modelling includes both run-of-river and reservoir projects, and it integrates advanced rules for calculating efficiencies of a variety of hydro turbines.

The small hydro power plant model can be utilized to assess small hydro power developments usually assorted under the following three terms:

- Small hydro
- Mini hydro
- Micro hydro

The small hydro power development model has been made mainly to find out if work on the small hydro power plant development should continue further or be cancelled in favor of other options. Each hydro location is specific, since about 75% of the project cost is defined by the site conditions. Only about 25% of the price is relatively fixed, being the price of production of the electromechanical parts and elements.

A flowchart of the typical numerical algorithms for small hydro power plant evaluation is displayed in Figure 1. User inputs involve the flow-duration curve and, for isolated-electricity network and off-grid purposes, the load-duration curve. Turbine efficiency is determined at regular intervals on the flow-duration curve. Plant power capacity is then evaluated and the power-duration curve is made. Usable energy is basically determined by integrating the power-duration curve. In the case of a central-transmission network, the energy produced is equal to the energy available. In the case of an isolated-transmission network or off-grid purpose, the process is slightly more sophisticated and includes both the power-duration curve and the load-duration curve.

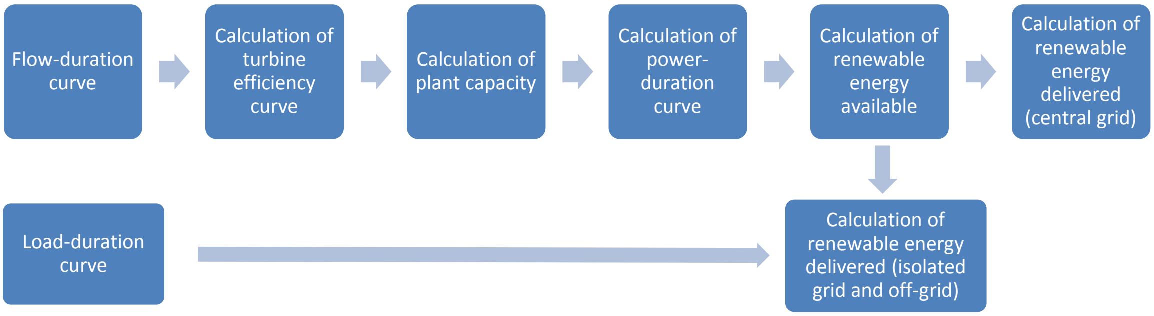

Figure 1. Small hydro energy model

There are few limitations to formulas shown below. First, the formulas have been made to assess run-of-river small hydro power developments. The assessment of storage developments is possible, however, a number of assumptions are needed. Changes in gross head due to variations in reservoir water level cannot be modelled. The model needs a unique value for gross head and, in the case of reservoir developments; an adequate average value must be defined. The determination of the mean head has to be done outside of the model and will need an understanding of the impacts of changes in head on annual power generation. Second, for isolated-transmission network and off-grid applications in isolated locations, the power demand has been assumed to follow the same pattern for every day of the year. For remote areas where power requirement and available power change significantly over the course of a year, modifications will have to be made to the calculated amount of renewable energy delivered. As will be seen in the next paragraphs, formulas condenses in an easy-to-use format a wealth of data, and it should be of great help to engineers involved in the initial assessment of small hydro power developments.

Hydrology

Hydrological information is defined as a flow-duration curve, which is assumed to represent the flow conditions in the river being suitable over the course of an average year. For storage developments, information must be defined by the user and should represent the regulated flow that results from operating a reservoir; at the moment, the head change with storage drawdown is not included in the model. For run-of-river developments, the needed flow-duration curve information can be defined either manually or by using the specific run-off methodology.

A flow-duration curve is a graph of the historical flow at a location ordered from maximum to minimum flow. The flow-duration curve is used to evaluate the predicted availability of flow over time, and accordingly the power and energy, at a location. The model then defines the firm flow that will be usable for electricity generation based on the flow-duration curve information, the percent time the firm flow should be available, and the residual flow.

Flow-duration curve

The flow-duration curve is defined by twenty-one values $Q_0, Q_5, \ldots . Q_{100}$ showing the flow on the flow-duration curve in 5% increments. In other words, Q_n represents the flow that is matched or exceeded n % of the time. An example of a flow-duration curve is given in Figure 2.

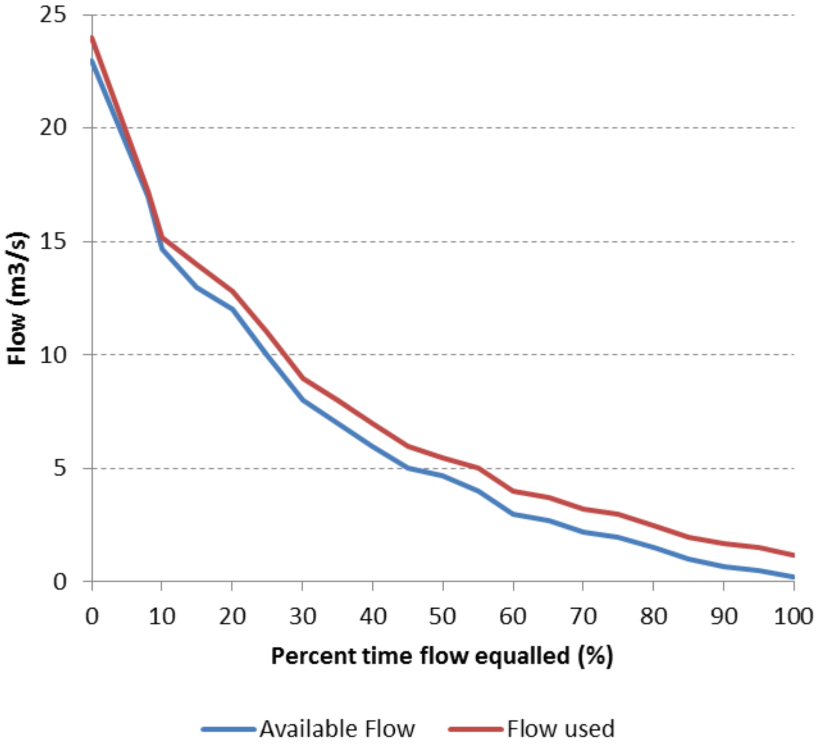

Figure 2. Flow duration curve

When the specific run-off methodology is utilized, the flow-duration curve is showed in a normalized form, i.e. relative to the average flow. The average flow Q is calculated as:

$$\bar{Q} = RA_D \qquad (1)$$

where R is the specific run-off and A_D is the drainage area. Then the actual flow information $Q_n(n = 0,5, \ldots .,100)$ is calculated from the normalized flow information q_n extracted from the weather database through:

$$Q_n = q_n\bar{Q} \qquad (2)$$

Available flow

Often, a certain quantity of flow must be left in the river throughout the year for environmental reasons. This residual flow Q_r is defined by the user and must be subtracted from all values of the flow-duration curve for the computation of plant size, firm capacity and renewable power available, as explained further on in this chapter. The usable flow $Q_n'(n = 0,5, \ldots.,100)$ is then determined by:

$$Q_n' = \max(Q_n - Q_r, 0) \qquad (3)$$

The usable flow-duration curve is displayed in Figure 2, with as an example Q_r set to $1\ m^3/s$.

Firm flow

The firm flow is determined as the flow being available p % of the time, where p is a percentage defined by the user and is typically equal to 95%. The firm flow is defined from the available flow-duration curve. If needed, a linear interpolation between 5% intervals is used to find the firm flow. In the example of Figure 2 the firm flow is equal to $1.5\ m^3/s$ with p set to 90%.

Load

The degree of sophistication used to define the load depends on the type of transmission network considered. If the small hydro power plant is interconnected to a central-grid, then it is assumed that the electricity network absorbs all of the power production and the load does not need to be defined. If on the other hand the system is off-grid or interconnected to an isolated-transmission network, then the part of the power that can be delivered depends on the load. Given methodology assumes that the daily load requirement is the same for all days of the year and can be represented by a load-duration curve. An example of such a curve is given in Figure 3. As for the flow-duration curve given in the previous section, the load-duration curve is defined by twenty-one values $L_0, L_5, \ldots., L_{100}$, defining the load on the load-duration curve in 5% increments; L_k represents the load that is equalled or exceeded k % of the time.

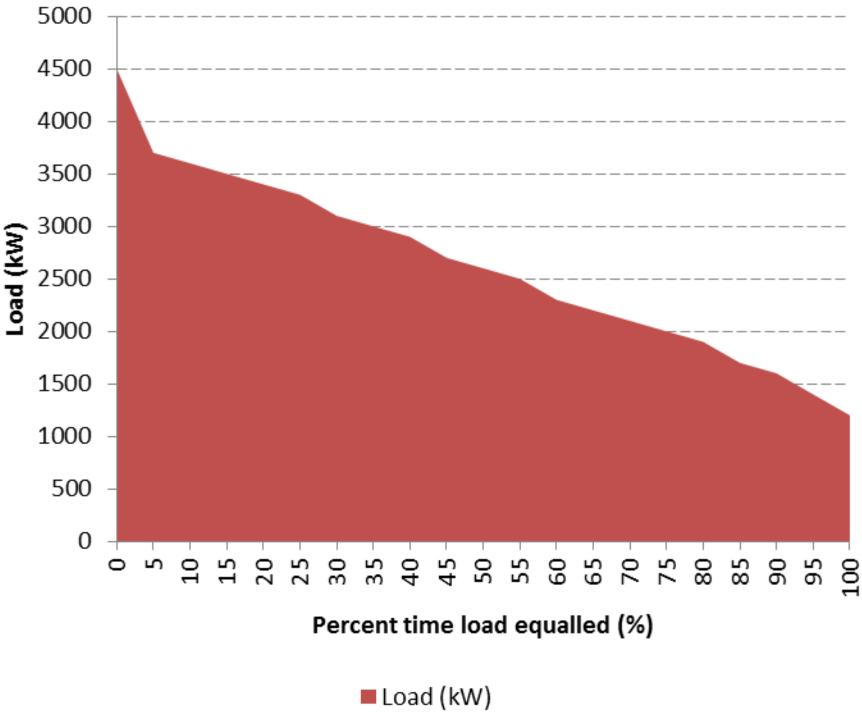

Figure 3. Load duration curve

Energy demand

Daily energy requirement is computed by integrating the area under the load-duration curve over one day. A simple trapezoidal integration method is used. The daily requirement D_d expressed in kWh is therefore computed as:

$$D_d = \sum_{k=1}^{20} \left(\frac{L_{5(k-1)} + L_{5k}}{2} \right) \frac{5}{100} 24 \qquad (4)$$

with the L expressed in kW. The annual energy requirement D is found by multiplying the daily requirement by the number of days in a year, 365:

$$D = 365 D_d \qquad (5)$$

Average load factor

The average load factor L is the ratio of the average daily load $(D_d/24)$ to the peak load(L_0):

$$\bar{L} = \frac{\frac{D_d}{24}}{L_0} \qquad (6)$$

This quantity is not utilized by the rest of the algorithm but is simply given to the user to provide an indication of the variability of the load.

Energy Generation

Given methodology provides estimated alternative energy delivered (MWh) based on the adjusted available flow (adjusted flow-duration curve), the design flow, the residual flow, the load (load-duration curve), the gross head and the efficiencies/ losses. The computation includes a comparison of the daily alternative energy available to the daily load-duration curve for each of the flow-duration curve figures.

Turbine efficiency curve

Small hydro turbine efficiency information can be defined manually or can be computed. Computed efficiencies can be adapted using the turbine manufacture/ design coefficient and the efficiency adjustment factor. Standard turbine efficiency curves have been formulated for the following turbine types:

- Kaplan (reaction turbine)
- Francis (reaction turbine)
- Propellor (reaction turbine)
- Pelton (impulse turbine)
- Turgo (impulse turbine)
- Cross-flow (generally classified as an impulse turbine).

Turbine type is defined based on its suitability to the available head and flow conditions. The computed turbine efficiency curves take into account a number of factors including rated head (gross head less maximum hydraulic losses), runner diameter, turbine specific speed and the turbine manufacture/design coefficient. The efficiency formulas were deducted from a large number of manufacture efficiency curves for different turbine models and head and flow conditions.

For various turbine applications it is assumed that all turbines are the same and that a single turbine will be utilized up to its maximum flow and then flow will be divided equally between two turbines, and so on up to the maximum number of turbines selected. The turbine efficiency formulas and the number of turbines are utilized to compute plant turbine efficiency from 0% to 100% of design flow (maximum plant flow) at 5% intervals. An example turbine efficiency curve is given in Figure 4 for 1 and 2 turbines.

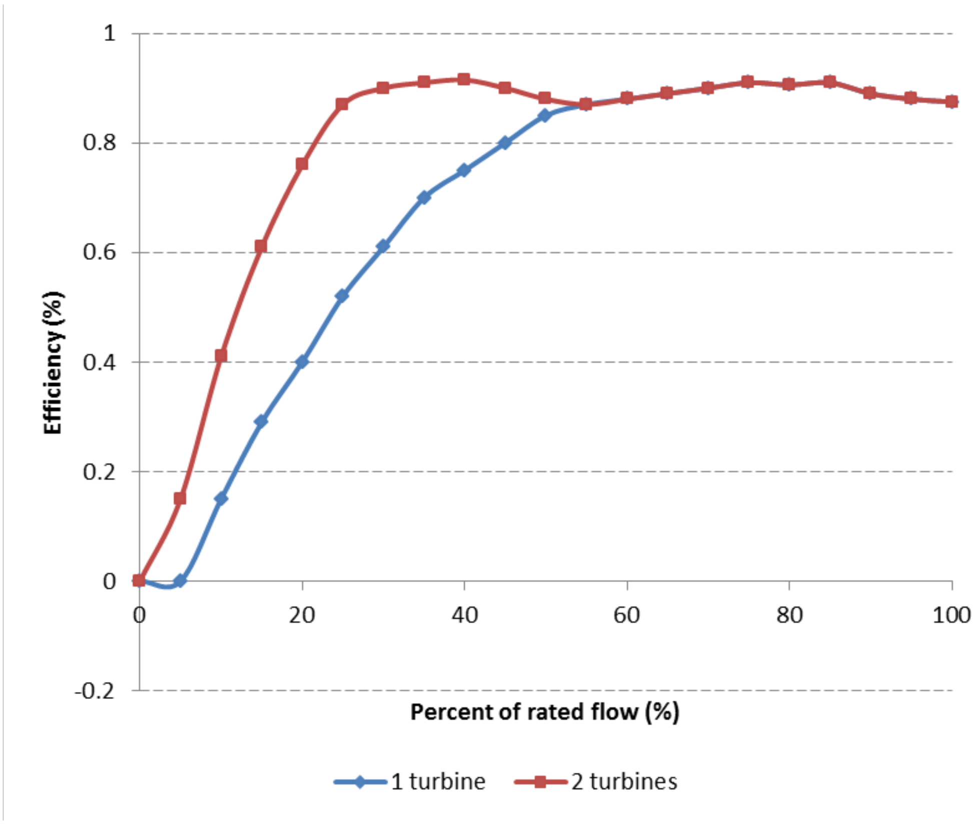

Figure 4. Computed efficiency curves for Francis turbine

Power available as a function of flow

Actual power P usable from the small hydro power plant at any given flow value Q is defined by the following formula, in which the flow-dependent hydraulic losses and tailrace reduction are taken into account:

$$P = \rho g Q\left[H_g - \left(h_{hydr} + h_{tail}\right)\right] e_t e_g (1 - l_{trans})\left(1 - l_{para}\right) \tag{7}$$

where ρ is the density of water (1,000 kg/m^3), g the acceleration of gravity (9.81 m/s^2),

H_g the gross head, h_{hydr} and h_{tail} are respectively the hydraulic losses and tailrace effect associated with the flow; and e_t is the turbine efficiency at flow Q. Finally, e_g is the generator efficiency, l_{trans} the transformer losses, and l_{para} the parasitic electricity losses e_g. l_{trans}, and l_{para} are determined by the user and are assumed independent from the considered flow. Hydraulic losses are adapted over the range of available flows based on the following formula:

$$h_{hydr} = H_g l_{hydr,max} \frac{Q^2}{Q_{des}^2} \tag{8}$$

where $l_{hydr,max}$ is the maximum hydraulic losses defined by the user, and Q_{des} the design flow. Similarly the maximum tailrace effect is adapted over the range of available flows with the following formula:

$$h_{tail} = h_{tail,max} \frac{(Q - Q_{des})^2}{(Q_{max} - Q_{des})^2} \tag{9}$$

where $h_{tail,max}$ is the maximum tailwater impact, i.e. the maximum decrease in available gross head that will occur during times of high flows in the river. Q_{max} is the maximum river flow, and equation (9) is used only to river flows that are higher than the plant design flow (i.e. when $Q > Q_{des}$).

Plant capacity

Plant capacity P_{des} is determined by re-writing formula (7) at the design flow Q_{des} . The formula simplifies to:

$$P_{des} = \rho g Q_{des} H_g (1 - l_{hydr}) e_{t,des} e_g (1 - l_{trans})(1 - l_{para}) \tag{10}$$

where P_{des} is the plant capacity and $e_{t,des}$ the turbine efficiency at design flow.

The small hydro plant firm capacity is defined again with formula (7), but this time using the firm flow and corresponding turbine efficiency and hydraulic losses at this flow. If the firm flow is higher than the design flow, firm plant capacity is set to the plant capacity computed through formula (10).

Power-duration curve

Computation of power usable as a function of flow, using formula (7) for all 21 values of the available flow $Q'_0, Q'_5, \ldots\ldots, Q'_{100}$ used to define the flow-duration curve, leads to 21 values of available power $P_0, P_1, \ldots\ldots, P_{100}$, defining a power-duration curve. Since the design flow is defined as the maximum flow that can be utilized by the turbine, the flow values utilized in formulas (7) and (8) are actually $Q_{n,used}$ determined as:

$$Q_{n,used} = \min(Q'_n, Q_{des}) \qquad (11)$$

An example power-duration curve is given in Figure 5, with the design flow equal to 3 m^3/s.

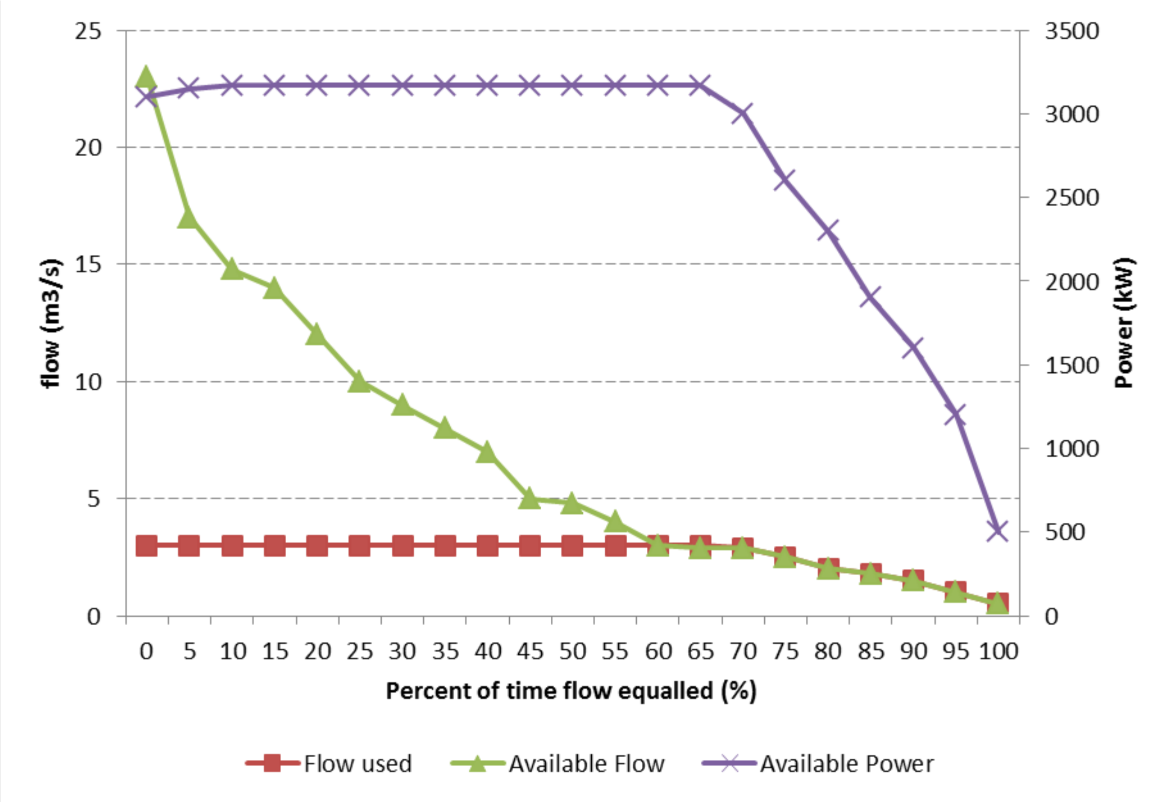

Figure 5. Power duration curve

Renewable energy available

Renewable energy available is defined by computing the area under the power curve assuming a straight-line between adjacent computed power output figures. Provided that the flow-duration curve represents an annual cycle, each 5% interval on the curve is equal to 5% of 8,760 hours (number of hours per year). The annual available energy E_{avail} (in kWh/yr) is therefore computed from the values P (in kW) by:

$$E_{avail} = \sum_{k=1}^{20} \left(\frac{P_{5(k-1)} + P_{5k}}{2} \right) \frac{5}{100} 8760 (1 - l_{dt}) \qquad (12)$$

where l_{dt} is the annual downtime losses as defined by the user. In the case where the design flow falls between two 5% increments on the flow-duration curve the interval is divided in two, and a linear interpolation is utilized on each side of the design flow.

Equation (12) determines the quantity of renewable energy available. The quantity actually delivered depends on the type of transmission network, as is presented in the following paragraphs.

Renewable energy delivered - central-grid

For central-grid use, it is assumed that the electricity grid is able to absorb all the energy generated by the small hydro power plant. Therefore, all the alternative energy available will be provided to the central-electricity grid and the renewable energy provided, E_{dlvd}, is simply:

$$E_{dlvd} = E_{avail} \qquad (13)$$

Renewable energy delivered - isolated-grid and off-grid

For isolated-electricity grid and off-grid developments the process is slightly more complex because the energy delivered is actually limited by the needs of the local electricity network or the load, as defined by the load-duration curve (Figure 3). The following process is utilized: for each 5% increase on the flow-duration curve, the corresponding available plant power production (assumed to be same over a day) is compared to the load-duration curve (assumed to represent the daily load requirement). The part of energy that can be provided by the small hydro power plant is defined as the area that is under both the load-duration curve and the horizontal line representing the available plant power generation. Twenty-one figures of the daily energy provided $G_0, G_1, \ldots\ldots, G_{100}$ corresponding to the available power $P_0, P_1, \ldots\ldots, P_{100}$ are computed. For each figure of usable power P_n, the daily energy provided G_n, is defined by:

$$G_n = \sum_{k=1}^{20} \left(\frac{P'_{n,5(k-1)} + P'_{n,5k}}{2} \right) \frac{5}{100} 24 \tag{14}$$

where $P'_{n,k}$ is the lesser of load L_k and usable power P_n :

$$P'_{n,k} = \min(P_n, L_k) \tag{15}$$

In the case where the available power $P'_{n,k}$ falls between two 5% increments on the load duration curve, the interval is split in two and a linear interpolation is used on each side of the available power.

This process is explained by an example, using the load-duration curve from Figure 3 and figures from the power-duration curve given in Figure 5. The aim of the example is to define the daily alternative energy G_{75} provided for a flow that is exceeded 75% of the time. Reference to Figure 5 should be made to define the corresponding power level:

$$P_{75} = 2{,}630\ kW \tag{16}$$

Then the resulting value should be reported as a horizontal line on the load-duration curve, as given in Figure 6. The area that is both under the load-duration curve and the horizontal line is the alternative energy provided per day for the plant capacity that matches to flow Q_{75}. Integration with equation (14) provides the result:

$$G_{75} = 56.6\ MWh/d \tag{17}$$

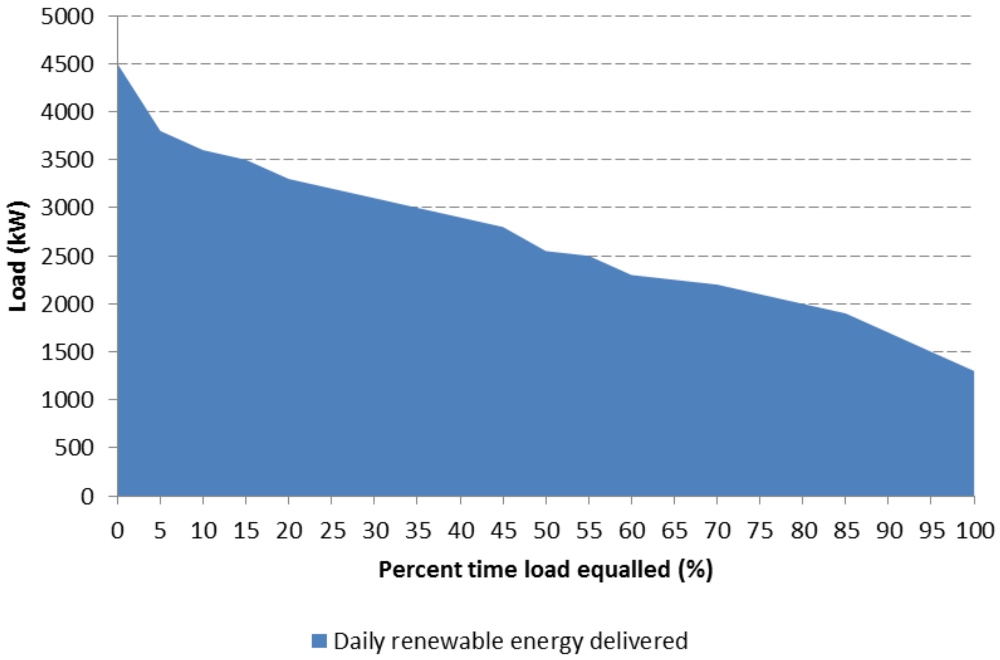

Figure 6. Calculation of daily renewable energy delivered

This process is repeated for all values $P_0, P_1, \ldots\ldots, P_{100}$ to find twenty one values of the daily alternative energy provided $G_0, G_1, \ldots\ldots, G_{100}$, as a function of percent time the flow is exceeded as given in Figure 7. The annual alternative energy provided, E_{dlvd}, is found simply by computing the area under the curve of Figure 7, again with a trapezoidal rule:

$$E_{dlvd} = \sum_{k=1}^{20} \left(\frac{G_{5(n-1)} + G_{5n}}{2} \right) \frac{5}{100} 365(1 - l_{dt}) \tag{18}$$

where, as before, l_{dt} is the annual downtime losses as defined by the user.

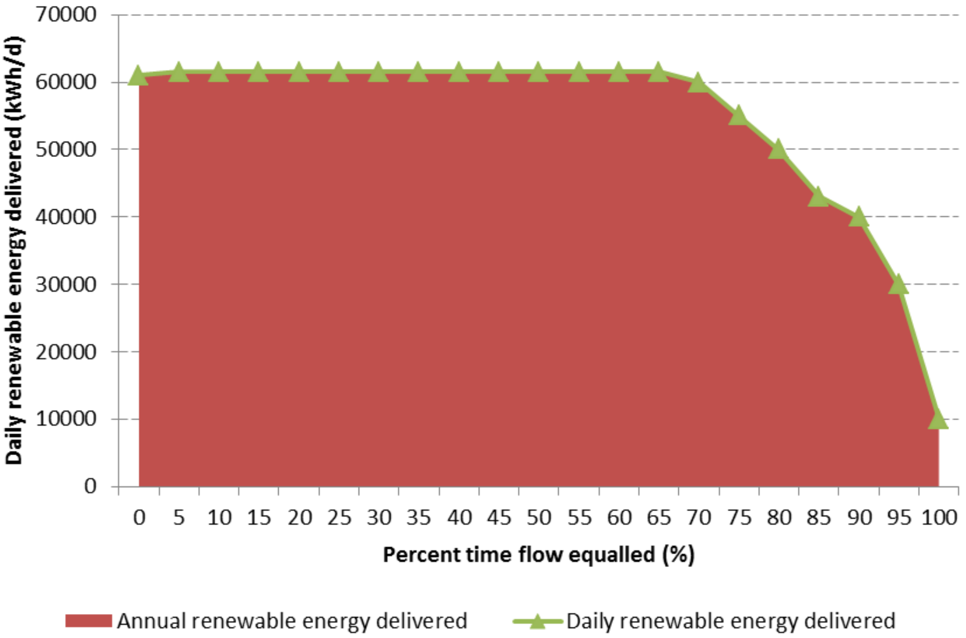

Figure 7. Calculation of annual renewable energy delivered

Small hydro plant capacity factor

The annual capacity factor K of the small hydro power plant is a measure of the available flow at the location and how efficiently it is utilized. It is determined as the average output of the plant in comparison to its rated capacity:

$$K = \frac{E_{dlvd}}{8760 P_{des}} \tag{19}$$

where the annual alternative energy provided, E_{dlvd}, computed through (13) or (18) is defined in kWh, and plant capacity computed through (10) is shown in kW.

Excess renewable energy available

Excess renewable energy available E_{excess}, is the difference between the alternative energy available E_{avail}, and the alternative energy provided E_{dlvd}:

$$E_{excess} = E_{avail} - E_{dlvd} \tag{20}$$

E_{avail} is computed through formula (12) and E_{dlvd} through either (13) or (18).

Summary

In this course, the computation method for small hydro power plant technical parameters has been presented in detail. Generic formulae enable the computation of turbine efficiency for a variety of turbines. These efficiencies, together with the flow-duration curve and (in the case of isolated-transmission network and off-transmission network developments) the load-duration curve, enable the computation of alternative energy provided by a proposed small hydro power plant. The condensed calculations enable the evaluation of development costs; alternatively, a detailed pricing methodology can be utilized. The process illustrated above is excellent for pre-feasibility stage assessments related to small hydro developments.

References:

Clean Energy Project Analysis RETScreen® Engineering & Cases Textbook, Third Edition, © Minister of Natural Resources Canada 2001-2005, September 2005