PDHonline Course E502 (3 PDH)

Small Hydro Project Analysis

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1. Small Hydro Project Analysis

This course covers the analysis of potential small hydro projects including a technology background. Project case studies are also included in the course.

2. Small Hydro Background

Hydroelectricity is one of the most mature forms of renewable energy, providing more than 19% of the world's electricity consumption from both large and small power plants. Countries such as Brazil, the United States, Canada and Norway produce significant amounts of electricity from very large hydroelectric facilities. However, there are also many regions of the world that have a significant number of small hydro power plants in operation. In China, for example, more than 19,000 MW of electricity is produced from 43,000 small hydro facilities.

There is no universally accepted definition of the term "small hydro" which, depending on local definitions can range in size from a few kilowatts to 50 megawatts or more of rated power output. Internationally, "small" hydro power plant capacities typically range in size from 1 MW to 50 MW, with projects in the 100 kW to 1 MW range sometimes referred to as "mini" hydro and projects under 100 kW referred to as "micro" hydro. Installed capacity, however, is not always a good indicator of the size of a project. For example, a 20 MW, low-head "small" hydro plant is anything but small as low-head projects generally use much larger volumes of water, and require larger turbines as compared with high-head projects.

3. Description of Small Hydro Power Plants

A small hydro generating station can be described under two main headings: civil works, and electrical and mechanical equipment.

4. Civil works

The main civil works of a small hydro development are the diversion dam or weir, the water passages and the powerhouse. The diversion dam or weir directs the water into a canal, tunnel, penstock or turbine inlet. The water then passes through the turbine, spinning it with enough force to create electricity in a generator. The water then flows back into the river via a tailrace. Generally, small hydro projects built for application at an isolated area are run-of-river developments, meaning that water is not stored in a reservoir and is used only as it is available. The cost of large water storage dams cannot normally be justified for small waterpower projects and consequently, a low dam or diversion weir of the simplest construction is normally used. Construction can be of concrete, wood, masonry or a combination of these materials. Considerable effort continues to be spent to lower the cost of dams and weirs for small hydro projects, as the cost of this item alone frequently renders a project not financially viable.

The water passages of a small hydro project comprise the following:

- An intake which includes trashracks, a gate and an entrance to a canal, penstock or directly to the turbine depending on the type of development. The intake is generally built of reinforced concrete, the trashrack of steel, and the gate of wood or steel.

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

- The entrance and exit of the turbine, which include the valves and gates necessary to shut off flow to the turbine for shutdown and maintenance. These components are generally made of steel or iron. Gates downstream of the turbine, if required for maintenance, can be made of wood.

- A tailrace, which carries the water from the turbine exit back to the river. The tailrace, like the canal, is excavated. The powerhouse contains the turbine or turbines and most of the mechanical and electrical equipment. Small hydro powerhouses are generally kept to the minimum size possible while still providing adequate foundation strength, access for maintenance, and safety. Construction is of concrete and other local building materials.

Simplicity in design, with an emphasis on practical, easily constructed civil structures is of prime concern for a small hydro project in order to keep costs at a minimum.

5. Electrical and mechanical equipment

The primary electrical and mechanical components of a small hydro plant are the turbine(s) and generator(s). A number of different types of turbines have been designed to cover the broad range of hydropower site conditions found around the world. Turbines used for small hydro applications are scaled-down versions of turbines used in conventional large hydro developments. Turbines used for low to medium head applications are usually of the reaction type and include Francis and fixed and variable pitch (Kaplan) propeller turbines. The runner or turbine “wheel” of a reaction turbine is completely submersed in water. Turbines used for high-head applications are generally referred to as impulse turbines. Impulse turbines include the Pelton, Turgo and crossflow designs. The runner of an impulse turbine spins in the air and is driven by a high-speed jet of water.

Small hydro turbines can attain efficiencies of about 90%. Care must be given to selecting the preferred turbine design for each application as some turbines only operate efficiently over a limited flow range (e.g. propeller turbines with fixed blades and Francis turbines). For most run-of-river small hydro sites where flows vary considerably, turbines that operate efficiently over a wide flow range are usually preferred (e.g. Kaplan, Pelton, Turgo and crossflow designs).

Alternatively, multiple turbines that operate within limited flow ranges can be used. There are two basic types of generators used in small hydro plants - synchronous or induction (asynchronous). A synchronous generator can be operated in isolation while an induction generator must normally be operated in conjunction with other generators. Synchronous generators are used as the primary source of power produced by utilities and for isolated diesel-grid and stand-alone small hydro applications. Induction generators with capacities less than about 500 kW are generally best suited for small hydro plants providing energy to a large existing electricity grid.

Other mechanical and electrical components of a small hydro plant include:

- Speed increaser to match the ideal rotational speed of the turbine to that of the generator (if required)
- Water shut-off valve(s) for the turbine(s)
- River by-pass gate and controls (if required)
- Hydraulic control system for the turbine(s) and valve(s)
- Electrical protection and control system
- Electrical switchgear
- Transformers for station service and power transmission
- Station service including lighting and heating and power to run control systems and switchgear
- Water cooling and lubricating system (if required)
- Ventilation system
- Backup power supply
- Telecommunication system
- Fire and security alarm systems (if required)
- Utility interconnection or transmission and distribution system

6. Small Hydro Project Development

The development of small hydro projects typically takes from 2 to 5 years to complete, from conception to final commissioning. This time is required to undertake studies and design work, to receive the necessary approvals and to construct the project. Once constructed, small hydro plants require little maintenance over their useful life, which can be well over 50 years. Normally, one part-time operator can easily handle operation and routine maintenance of a small hydro plant, with periodic maintenance of the larger components of a plant usually requiring help from outside contractors.

The technical and financial viability of each potential small hydro project are very site specific. Power output depends on the available water (flow) and head (drop in elevation). The amount of energy that can be generated depends on the quantity of water available and the variability of flow throughout the year.

The economics of a site depends on the power (capacity) and the energy that a project can produce, whether or not the energy can be sold, and the price paid for the energy. In an isolated area (off-grid and isolated-grid applications) the value of energy generated for consumption is generally significantly more than for systems that are connected to a central-grid. However, isolated areas may not be able to use all the available energy from the small hydro plant and, may be unable to use the energy when it is available because of seasonal variations in water flow and energy consumption.

A conservative, “rule-of-thumb” relationship is that power for a hydro project is equal to seven times the product of the flow (Q) and gross head (H) at the site ($P = 7QH$). Producing 1 kW of power at a site with 100 m of head will require one-tenth the flow of water that a site with 10 m of head would require. The hydro turbine size depends primarily on the flow of water it has to accommodate. Thus, the generating equipment for higher-head, lower-flow installations is generally less expensive than for lower-head, higher-flow plants.

The same cannot necessarily be said for the civil works components of a project which are related much more to the local topography and physical nature of a site.

7. Types of small hydro developments

Small hydro projects can generally be categorised as either “run-of-river developments” or “water storage (reservoir) developments”.

8. Run-of-river developments

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

The power output of run-of-river small hydro plants fluctuates with the hydrologic cycle, so they are often best suited to provide energy to a larger electricity system. Individually, they do not generally provide much firm capacity. Therefore, isolated areas that use small hydro resources often require supplemental power. A run-of-river plant can only supply all of the electrical needs of an isolated area or industry if the minimum flow in the river is sufficient to meet the load’s peak power requirements.

Run-of-river small hydro can involve diversion of the flow in a river. Diversion is often required to take advantage of the drop in elevation that occurs over a distance in the river. Diversion projects reduce the flow in the river between the intake and the powerhouse. A diversion weir or small dam is usually required to divert the flow into the intake.

9. Water storage (reservoir) developments

For a hydroelectric plant to provide power on demand, either to meet a fluctuating load or to provide peak power, water must be stored in one or more reservoirs. Unless a natural lake can be tapped, providing storage usually requires the construction of a dam or dams and the creation of new lakes. This impacts the local environment in both negative and positive ways, although the scale of development often magnifies the negative impacts. This often presents a conflict, as larger hydro projects are attractive because they can provide "stored" power during peak demand periods. Due to the economies of scale and the complex approval process, storage schemes tend to be relatively large in size.

The creation of new storage reservoirs for small hydro plants is generally not financially viable except, possibly, at isolated locations where the value of energy is very high. Storage at a small hydro plant, if any, is generally limited to small volumes of water in a new head pond or existing lake upstream of an existing dam. Pondage is the term used to describe small volumes of water storage. Pondage can provide benefits to small hydro plants in the form of increased energy production and/or increased revenue. Another type of water storage development is "pumped storage" where water is "recycled" between downstream and upstream storage reservoirs.

Water is passed through turbines to generate power during peak periods and pumped back to the upper reservoir during off-peak periods. The economics of pumped storage projects depends on the difference between the values of peak and off-peak power. Due to the inefficiencies involved in pumping versus generating, the recycling of water results in a net consumption of energy. Energy used to pump water has to be generated by other sources.

The environmental impacts that can be associated with small hydro developments can vary significantly depending on the location and configuration of the project.

The effects on the environment of developing a run-of-river small hydro plant at an existing dam are generally minor and similar to those related to the expansion of an existing facility. Development of a run-of-river small hydro plant at an undeveloped site can pose additional environmental impacts. A small dam or diversion weir is usually required. The most economical development scheme might involve flooding some rapids upstream of the new small dam or weir.

The environmental impacts that can be associated with hydroelectric developments that incorporate water storage (typically larger in size) are mainly related to the creation of a water storage reservoir. The creation of a reservoir involves the construction of a relatively large 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 use of water stored in the reservoir behind a dam or in a lake results in the fluctuation of water levels and flows in the river downstream. A rigorous environmental assessment is typically required for any project involving water storage.

10.Hydro project engineering phases

There are normally four phases for engineering work required to develop a hydro project. Note, however, that for small hydro, the engineering work is often reduced to three phases in order to reduce costs. Generally, a preliminary investigation is undertaken that combines the work involved in the first two phases described below.

The work, however, is completed to a lower level of detail in order to reduce costs. While reducing the engineering work increases the risk of the project not being financially viable, this can usually be justified due to the lower costs associated with smaller projects.

11.Reconnaissance surveys and hydraulic studies

This first phase of work frequently covers numerous sites and includes: map studies; delineation of the drainage basins; preliminary estimates of flow and floods; and a one day site visit to each site (by a design engineer and geologist or geotechnical engineer); preliminary layout; cost estimates (based on formulae or computer data) and final ranking of sites based on power potential; and an index of cost.

12.Pre-feasibility study

Work on the selected site or sites would include: site mapping and geological investigations (with drilling confined to areas where foundation uncertainty would have a major effect on costs); a reconnaissance for suitable borrow areas (e.g. for sand and gravel); a preliminary layout based on materials known to be available; preliminary selection of the main project characteristics (installed capacity, type of development, etc.); a cost estimate based on major quantities; the identification of possible environmental impacts; and production of a single volume report on each site.

13.Feasibility study

Work would continue on the selected site with a major foundation investigation programme; delineation and testing of all borrow areas; estimation of diversion, design and probable maximum floods; determination of power potential for a range of dam heights and installed capacities for project optimisation; determination of the project design earthquake and the maximum credible earthquake; design of all structures in sufficient detail to obtain quantities for all items contributing more than about 10% to the cost of individual structures; determination of the dewatering sequence and project schedule; optimisation of the project layout, water levels and components; production of a detailed cost estimate; and finally, an economic and financial evaluation of the project including an assessment of the impact on the existing electrical grid along with a multi-volume comprehensive feasibility report.

14.System planning and project engineering

This work would include studies and final design of the transmission system; integration of the transmission system; integration of the project into the power network to determine precise operating mode; production of tender drawings and specifications; analysis of bids and detailed design of the project; production of detailed construction drawings and review of manufacturer’s equipment drawings. However, the scope of this phase would not include site supervision nor project management, since this work would form part of the project execution costs.

15.Small Hydro Project Modelling

Small hydro project modelling provides a means to assess the available energy at a potential small hydro site that could be provided to a central-grid or, for isolated loads, the portion of this available energy that could be harnessed by a local electric utility (or used by the load in an off-grid system). Modelling addresses both run-of-river and reservoir developments, and it incorporates sophisticated formulae for calculating efficiencies of a wide variety of hydro turbines.

The small hydro model can be used to evaluate small hydro projects typically classified under the following three names:

- Small hydro
- Mini hydro
- Micro hydro

The small hydro project model has been developed primarily to determine whether work on the small hydro project should proceed further or be dropped in favour of other alternatives. Each hydro site is unique, since about 75% of the development cost is determined by the location and site conditions. Only about 25% of the cost is relatively fixed, being the cost of manufacturing the electromechanical equipment.

A flowchart of the typical calculation algorithms for small hydro power plant assessment is shown in Figure 1. User inputs include the flow-duration curve and, for isolated-grid and off-grid applications, the load-duration curve. Turbine efficiency is calculated at regular intervals on the flow-duration curve. Plant capacity is then calculated and the power-duration curve is established. Available energy is simply calculated by integrating the power-duration curve. In the case of a central-grid, the energy delivered is equal to the energy available. In the case of an isolated-grid or off-grid application, the procedure is slightly more complicated and involves both the power-duration curve and the load-duration curve.

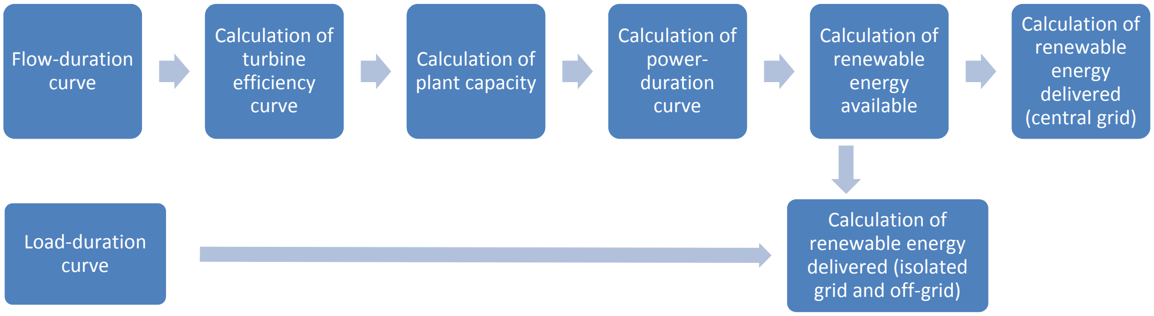

Figure 1. Small hydro energy model

There are some limitations to equations presented below. First, the equations have been designed primarily to evaluate run-of-river small hydro projects. The evaluation of storage projects is possible, however, a number of assumptions are required. Variations in gross head due to changes in reservoir water level cannot be simulated. The model requires a single value for gross head and, in the case of reservoir projects, an appropriate average value must be entered.

The determination of the average head must be done outside of the model and will require an understanding of the effects of variations in head on annual energy production. Second, for isolated-grid and off-grid applications in isolated areas, the energy demand has been assumed to follow the same pattern for every day of the year. For isolated locations where energy demand and available energy vary significantly over the course of a year, adjustments will have to be made to the estimated amount of renewable energy delivered. As will be seen in the next sections, equations condenses in an easy-to-use format a wealth of information, and it should be of great assistance to engineers involved in the preliminary evaluation of small hydro projects.

16.Hydrology

Hydrological data are specified as a flow-duration curve, which is assumed to represent the flow conditions in the river being studied over the course of an average year. For storage projects, data must be specified by the user and should represent the regulated flow that results from operating a reservoir; at present, the head variation with storage drawdown is not included in the model. For run-of-river projects, the required flow-duration curve data can be specified either manually or by using the specific run-off method.

A flow-duration curve is a graph of the historical flow at a site ordered from maximum to minimum flow. The flow-duration curve is used to assess the anticipated availability of flow over time, and consequently the power and energy, at a site. The model then calculates the firm flow that will be available for electricity production based on the flow-duration curve data, the percent time the firm flow should be available and the residual flow.

17.Flow-duration curve

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

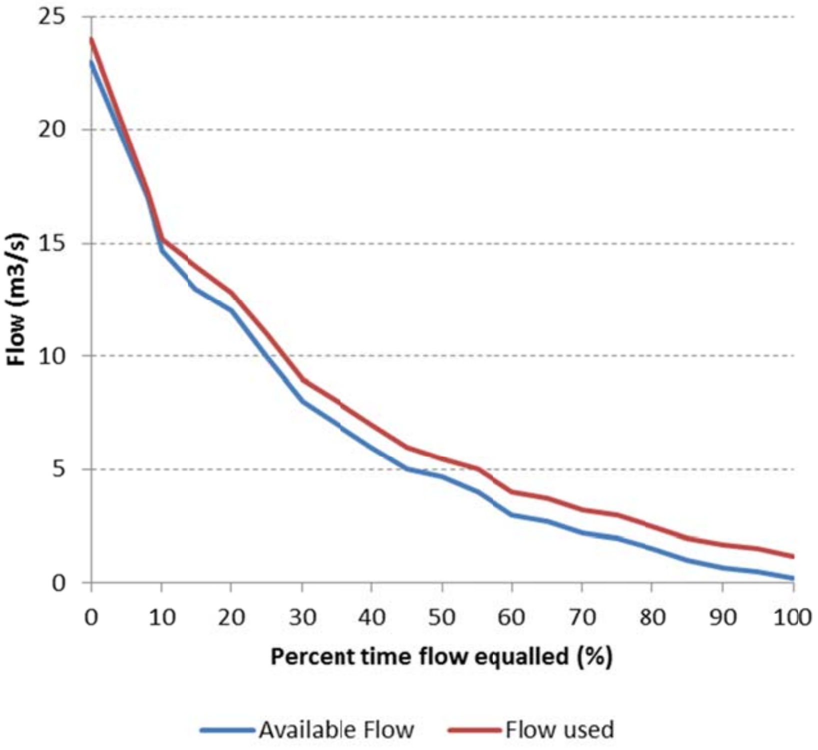

Figure 2. Example of flow duration curve

When the specific run-off method is used, the flow-duration curve is expressed in normalised form, i.e. relative to the mean flow. The mean flow Q is calculated as:

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

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

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

18.Available flow

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

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

The available flow-duration curve is shown in Figure 2, with as an example Q_r set to1 m^3/s.

19.Firm flow

The firm flow is defined as the flow being available p % of the time, where p is a percentage specified by the user and usually equal to 95%. The firm flow is calculated from the available flow-duration curve. If necessary, 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%.

20.Load

The degree of sophistication used to describe the load depends on the type of grid considered. If the small hydro power plant is connected to a central-grid, then it is assumed that the grid absorbs all of the energy production and the load does not need to be specified. If on the other hand the system is off-grid or connected to an isolated-grid, then the portion of the energy that can be delivered depends on the load. Presented methodology assumes that the daily load demand 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 shown in Figure 3. As for the flow-duration curve shown in previous section, the load-duration curve is specified 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.

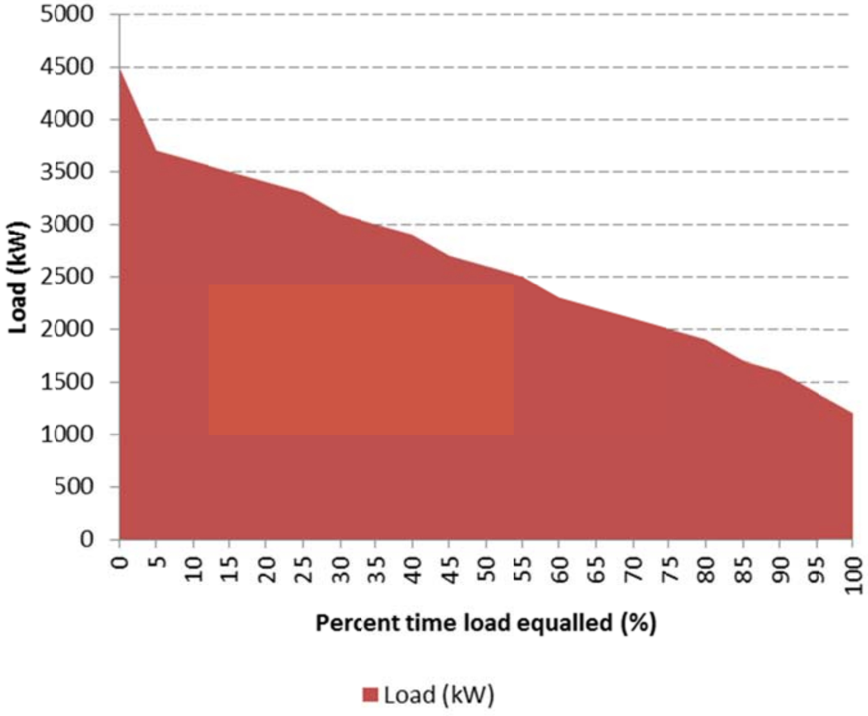

Figure 3. Example of a load duration curve

21.Energy demand

Daily energy demand is calculated by integrating the area under the load-duration curve over one day. A simple trapezoidal integration formula is used. The daily demand D_d expressed in kWh is therefore calculated 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 demand D is obtained by multiplying the daily demand by the number of days in a year, 365:

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

22. 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 used by the rest of the algorithm but is simply provided to the user to give an indication of the variability of the load.

23. Energy Production

Presented methodology presents estimated renewable 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 calculation involves comparing the daily renewable energy available to the daily load-duration curve for each of the flow-duration curve values.

24. Turbine efficiency curve

Small hydro turbine efficiency data can be specified manually or can be calculated. Calculated efficiencies can be adjusted using the turbine manufacture/design coefficient and efficiency adjustment factor. Standard turbine efficiencies curves have been developed 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).

The type of turbine is selected based on its suitability to the available head and flow conditions. The calculated turbine efficiency curves take into account a number of factors including rated head (gross head less maximum hydraulic losses), runner diameter (calculated), turbine specific speed (calculated for reaction turbines) and the turbine manufacture/design coefficient. The efficiency equations were derived from a large number of manufacture efficiency curves for different turbine types and head and flow conditions.

For multiple turbine applications it is assumed that all turbines are identical and that a single turbine will be used 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 equations and the number of turbines are used to calculate plant turbine efficiency from 0% to 100% of design flow (maximum plant flow) at 5% intervals. An example turbine efficiency curve is shown in Figure 4 for 1 and 2 turbines.

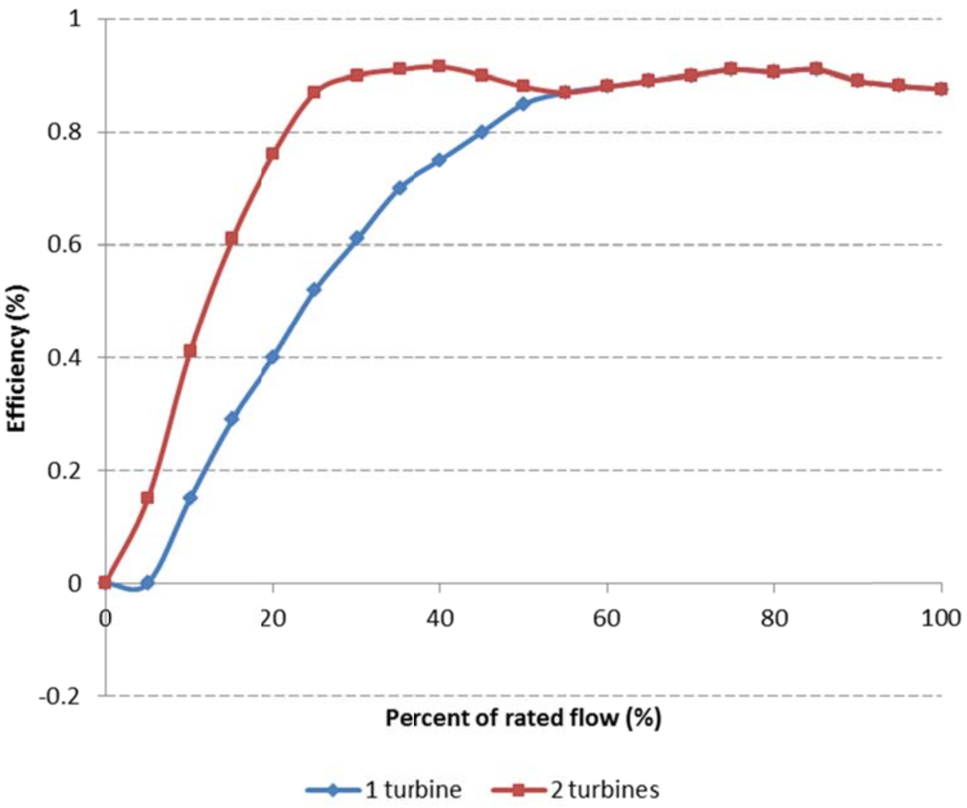

Figure 4. Calculated efficiency curves for Francis turbine

25.Power available as a function of flow

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

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

where ρ is the density of water (1,000 kg/m3), g the acceleration of gravity (9.81 m/s2), 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 flow considered. Hydraulic losses are adjusted over the range of available flows based on the following relationship:

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

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

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

where $h_{tail,max}$ is the maximum tailwater effect, i.e. the maximum reduction 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 applied only to river flows that are greater than the plant design flow (i.e. when $Q > Q_{des}$).

26.Plant capacity

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

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

where P_{des} is the plant capacity and $e_{t,des}$ the turbine efficiency at design flow. The small hydro plant firm capacity is calculated again with equation (7), but this time using the firm flow and corresponding turbine efficiency and hydraulic losses at this flow. If the firm flow is greater than the design flow, firm plant capacity is set to the plant capacity calculated through equation (10).

27.Power-duration curve

Calculation of power available as a function of flow using equation (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 used by the turbine, the flow values used in equations (7) and (8) are actually $Q_{n,used}$ defined as:

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

An example power-duration curve is shown in Figure 5, with the design flow equal to 3 m3/s.

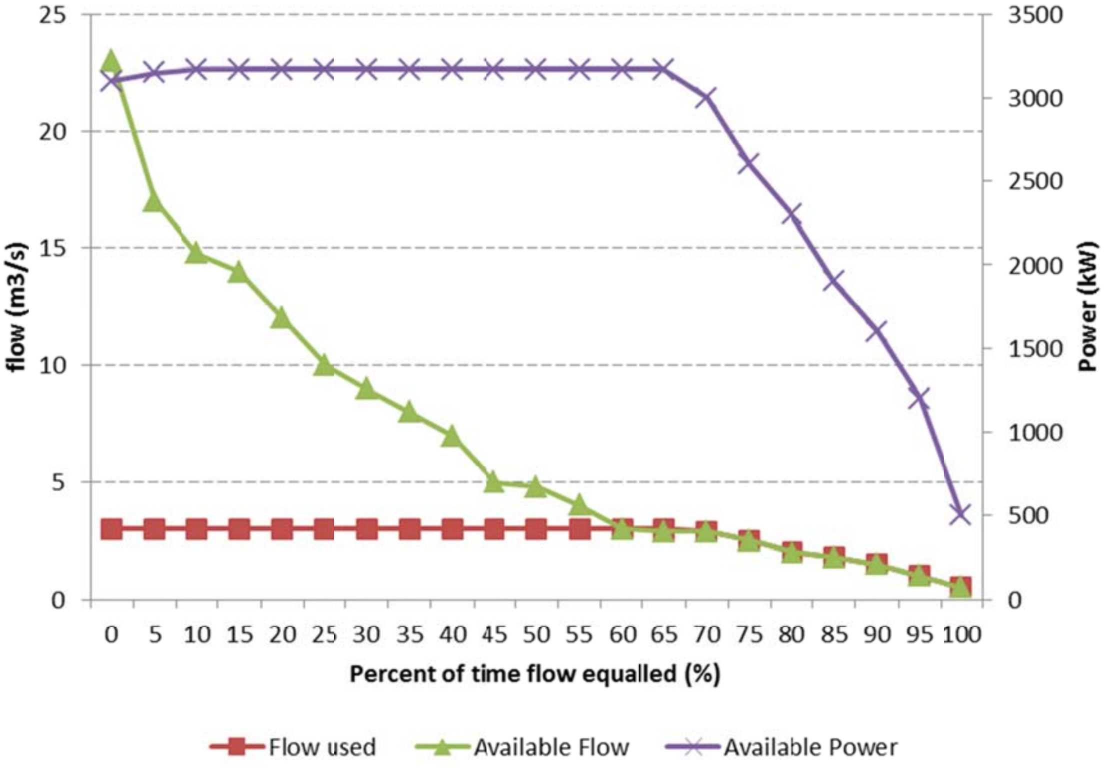

Figure 5. Example of a power duration curve

28.Renewable energy available

Renewable energy available is determined by calculating the area under the power curve assuming a straight-line between adjacent calculated power output values. Given that the flow-duration curve represents an annual cycle, each 5% interval on the curve is equivalent to 5% of 8,760 hours (number of hours per year). The annual available energy E_{avail} (in kWh/yr) is therefore calculated 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 specified by the user. In the case where the design flow falls between two 5% increments on the flow-duration curve the interval is split in two and a linear interpolation is used on each side of the design flow.

Equation (12) defines the amount of renewable energy available. The amount actually delivered depends on the type of grid, as is described in the following sections.

29. Renewable energy delivered - central-grid

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

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

30. Renewable energy delivered - isolated-grid and off-grid

For isolated-grid and off-grid applications the procedure is slightly more complicated because the energy delivered is actually limited by the needs of the local grid or the load, as specified by the load-duration curve (Figure 3). The following procedure is used: for each 5% increment on the flow-duration curve, the corresponding available plant power output (assumed to be constant over a day) is compared to the load-duration curve (assumed to represent the daily load demand). The portion of energy that can be delivered by the small hydro plant is determined as the area that is under both the load-duration curve and the horizontal line representing the available plant power output. Twenty-one values of the daily energy delivered $G_0, G_1, \ldots\ldots, G_{100}$ corresponding to available power $P_0, P_1, \ldots\ldots, P_{100}$ are calculated. For each value of available power P_n, , daily energy delivered G_n, is given by:

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

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

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

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.

The procedure is illustrated by an example, using the load-duration curve from Figure 3 and values from the power-duration curve shown in Figure 5. The purpose of the example is to determine the daily renewable energy G_{75} delivered for a flow that is exceeded 75% of the time. One first refers to Figure 5 to determine the corresponding power level:

$$P_{75} = 2{,}630 \text{ kW} \qquad (16)$$

Then one reports that number as a horizontal line on the load-duration curve, as shown in Figure 6. The area that is both under the load-duration curve and the horizontal line is the renewable energy delivered per day for the plant capacity that corresponds to flow Q_{75} integration with formula (14) gives the result:

$$G_{75} = 56.6 \text{ MWh/d} \qquad (17)$$

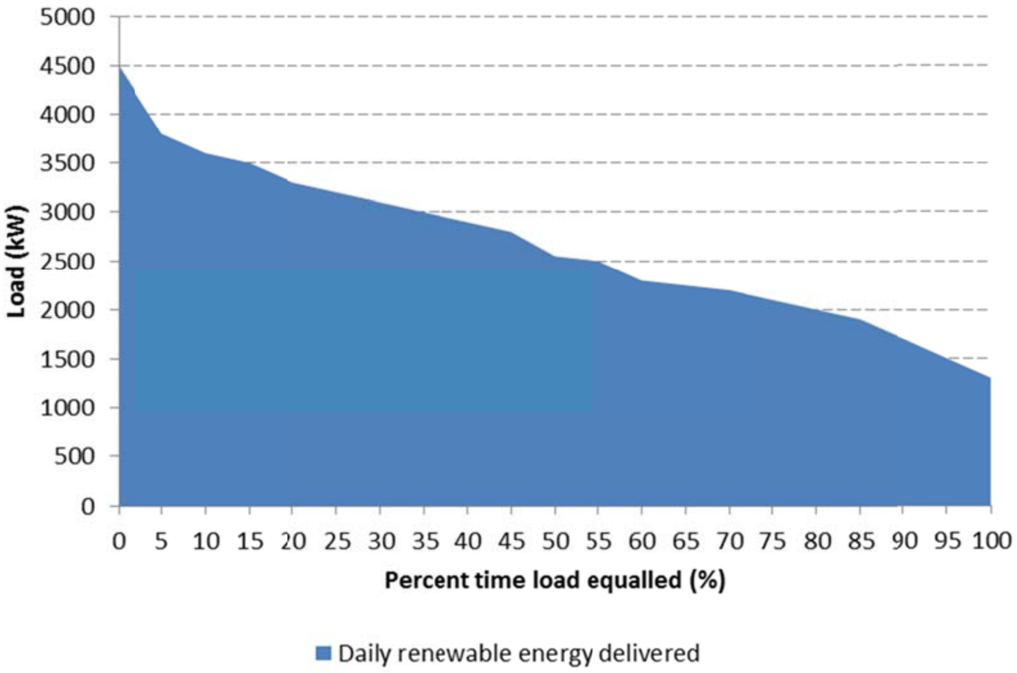

Figure 6. Example of calculation of daily renewable energy delivered

The procedure is repeated for all values $P_0, P_1, \ldots\ldots, P_{100}$ to obtain twenty one values of the daily renewable energy delivered $G_0, G_1, \ldots\ldots, G_{100}$, as a function of percent time the flow is exceeded as shown in Figure 7. The annual renewable energy delivered E_{dlvd}, is obtained simply by calculating 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 specified by the user.

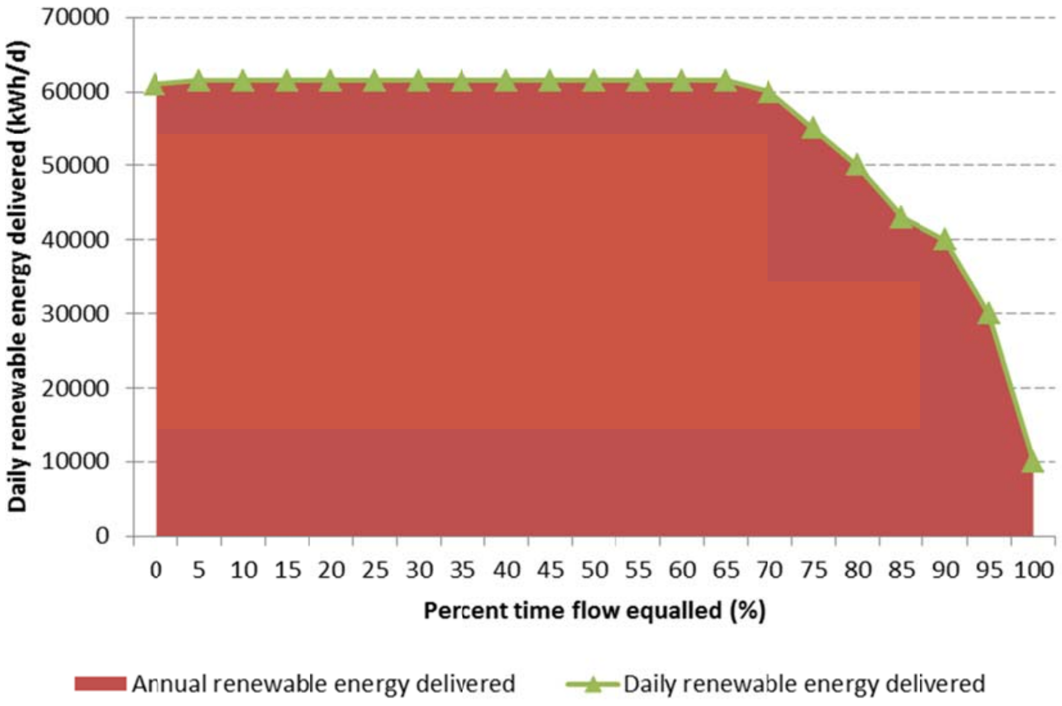

Figure 7. Example of calculation of annual renewable energy delivered

31.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 site and how efficiently it is used. It is defined as the average output of the plant compared to its rated capacity:

$$K = \frac{E_{dlvd}}{8760P_{des}} \qquad (19)$$

where the annual renewable energy delivered E_{dlvd}, calculated through (13) or (18) is expressed in kWh, and plant capacity calculated through (10) is expressed in kW.

32.Excess renewable energy available

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

$$E_{excess} = E_{avail} - E_{dlvd} \qquad (20)$$

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

33.Summary

Calculation methodology for small hydro power plant technical parameters has been shown in detail. Generic formulae enable the calculation of turbine efficiency for a variety of turbines. These efficiencies, together with the flow-duration curve and (in the case of isolated-grid and off-grid applications) the load-duration curve, enable the calculation of renewable energy delivered by a proposed small hydro power plant. Condensed formulae enable the estimation of project costs; alternatively, a detailed costing method can be used. Presented methodology is excellent for pre-feasibility stage studies for small hydro projects.