Hydropower schemes:
Generic principles of design and layout

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Author: Adrian Clayton

Mann Power Consulting Ltd.
Manor Farm
Kirkham Abbey
York
YO60 7JS
01653 619968
info@mannpower-hydro.co.uk
www.mannpower-hydro.co.uk

1. Introduction: the layout of a hydropower scheme

A number of quite different types of machinery can be used to generate hydroelectricity. The present document explains some common distinctions between types of site, general principles common to various equipment types, and considerations specific to the Archimedean screw system in which Mann Power Consulting Ltd specialises. The application of these principles at the present site is fully described in the accompanying Design & Access Statement.

This document deals primarily with the principles of the shape and location of a hydropower scheme in terms of how it interacts with its physical environment (land and water). Specifics relating to non-physical environmental impacts are addressed in other documents.

2. The physics of hydropower

Hydroelectric power requires that water must fall over a height. Energy is captured from the falling water. Note therefore that wave and tidal power are NOT hydroelectric power in this sense.

To capture energy from falling water, it is necessary to intercept it with a generating device at a point where the water can fall. This means either:

- finding an existing fall in height, such as a dam, weir or waterfall - or
- creating a fall in height, by constructing a weir, and/or
- causing water to flow out of the river, and leading it onward at a gentler slope than the main river, to a point where it is now higher above the main river.

Two main factors govern the energy which can be captured:

- Head: the height which the water can fall at this spot (in metres)
- Flow: the rate of water passing this spot (in tonnes per second or m^3/s)

It should be noted that flow is NOT speed or velocity. The same flow will move quickly through a narrow channel and slowly through a wide channel. Velocity (in m/s) is flow divided by cross-sectional area. The velocity of the water will vary as it moves through the system, and must be controlled by the design of the channels so that it does not cause erosion or other detriment.

The total power (in kilowatts kW) which could be exerted by falling water in a perfect system would equal the head times the flow times the force of gravity. In an imperfect world it is not possible to convert all that power into electrical power, and the shortfall is represented by an efficiency percentage. In micro-hydro this has often been found to be around 70%.

[equation: Power (kW) = Head (m) x Flow (m^3/s) x gravity (9.81 m/s^2) x efficiency (70%)]

Therefore the highest power of any system (its rated capacity) depends on the fall (head) and the quantity per second (flow) which can be taken.

3. Power vs energy

Power expressed in the terms above is a measure of just how big the system is – its capacity to generate. As such it does not tell us how productive the scheme is. A simple illustration in familiar terms might be the demand of an electric kettle: it may have a rated power of 1kW, but it consumes no electricity until it is actually switched on.

Similarly a hydropower scheme may have a rated power of 100kW - based on having been designed to drop a certain flow down a certain head at a certain efficiency. But the turbine will produce nothing each day unless the water flow is present. Therefore good design of the scheme ensures the turbine is positioned and sized to take an amount of water which is regularly present.

This may be likened to the challenge facing homeowners installing micro-wind turbines. Even if a turbine has been rated as achieving 10kW under design conditions, it can easily be positioned where it will never catch the necessary windspeeds and if so it can only disappoint.

The kW power rating of a scheme is therefore a useful indicator of its relative size. However, for energy planning and for assessing profitability, what is far more important is how much energy a system actually produces each day or each year. This output is measured in kilowatt-hours (kWh), which is what we pay for in our electricity bills. It will be appreciated that a well-designed or well-situated hydro system with a low rated capacity (max kW) could produce more electricity each year (kWh) than a system nominally bigger in kW terms but which lacked the expected water flow.

For this reason, judging the merits of generation schemes based on their maximum rated power (kW) can lead to perverse outcomes. Considering their actual productivity (kWh) is to be preferred. Calculation of CO_2 savings is also based on the latter.

4. Choice of a site > choice of equipment

For wind turbines, efficiency means siting them in locations where they can be reliably reached by non-turbulent wind and designing them for the windspeeds prevailing there. The equivalent considerations for hydropower are that there is a fall in height and that a certain flow can be expected to be present often enough to make the choice of a particular turbine size worthwhile.

The choice of a hydropower site is driven by interest from an investor or a long-term owner who has come to see the potential for hydropower at a particular place where there is a fall in the landscape. In such cases the applicant is exercising an entitlement to economically exploit a property in a way which that specific site particularly favours, rather than proposing a generic commercial project whose location is a matter of negotiable preference. This bears on the question of “better alternative sites” in planning terms, as the only suitable sites for hydropower are those where water falls.

Sites may be differentiated simply into those which are high-head and those which are low-head. This distinction is important because the two extremes dictate the use of different machinery and have different layouts, placing different emphases on their environmental impacts. A typical developer either has a high-head or a low-head site, and makes decisions accordingly. “Low head” tends to mean a fall of below 20m, such as the present site. Low head sites are discussed overleaf.

Some high-head schemes involve the creation of (or the use of existing) dams to obtain head. Schemes which do not artificially hold back the flow are labelled run-of-river, whereby flowing water is abstracted from a watercourse and allowed to fall through a system and back to the watercourse.

High-head schemes tend to bring the water inside a pressure pipe down to a turbine house. The turbine (and its house) can be small, because the flow can be small if the head is large. Small high-speed turbines such as Turgo and Pelton wheels and some Francis designs are associated with high-head schemes. Pressure effects and pipe integrity are important considerations. Because such schemes may require water to be led long distances from the watercourse to achieve the desired head, their environmental impacts may include long reaches of the watercourse which are depleted of their natural flow, and the impacts of creating long access roads to maintain an intake structure and pipework far away from the powerhouse. Pressure pipes and high-speed turbine rotation mean vertebrates must be totally screened out, and particles will damage the equipment if not filtered out. However, upland streams are often short and fishless, hence ecological impacts may be limited.

Low-head schemes may also conduct water through pipes, though often in open channels, and in most cases for a distance not exceeding 200m. As the head is so much lower, more flow must be taken to obtain viable performance. This means that channels/pipes and the turbine itself must be larger, sometimes requiring a larger powerhouse. Relevant turbines include crossflow, Francis, Kaplan and other propeller types, Archimedean screws, and waterwheels may also appear in use. The fineness of screening will have an impact on performance. At the lowest heads, pressure is not a consideration and fine screening may be dispensed with in the case of fish-compatible devices (Archimedean screw, waterwheels). Distances are shorter and overall footprint smaller than for high-head, but the watercourse is depleted of more water for a shorter distance. Lowland river habitats may be rich in fish and regulators often have aspirations for further improvement. Therefore schemes are often required to retain or improve the opportunities for fish to move past the site.

Frequently it is the case (particularly with low-head) that the site in question is prone to flooding. This is unsurprising, as hydropower installations are the technical successors of watermills, which in order to derive their power from the river must by their very nature lie within or close to its flood corridor. The argument must be that this is truly water-compatible development, as it is dependent upon and purposely sited to exploit water flows. As a general rule it should be noted that an installation which is designed to make use of a head of water at a weir is therefore by definition located at a fall in the terrain. The behaviour of flood water will differ by site, but it is unlikely to be higher below the fall than above. Schemes taking smaller flows will tend to make less imposition, but mitigation should be proportionate to any risk which is assessed. Schemes diverting water through open channels can logically only be located within the flood zone, as to convey open water outside it would simply extend the zone.

A potential developer will often approach a hydropower design consultant to advise on the potential of a given site. Such consultancy concerns itself with presenting options to the developer to determine which is most desirable in the light of economic, regulatory, and other expectations. Using a consultant is now more typical than DIY, because the electricity Feed-In Tariff is only available if designer and equipment are accredited for hydropower under the national MCS scheme.

As a developer is typically quite committed to the particular site in question, it is often possible to find viable means to incorporate mitigation for potential impacts which the scheme may pose. Thus environmental regulators (e.g. EA in England & Wales) are able to positively describe as “win-win” scenarios those which can fund fisheries improvements which further the aims of the regulator.

5. Use of the Archimedean screw

A relatively novel technology for low-head hydropower sites is the application of the Archimedean screw, a device which has been used in this role since 1997. The construction of the screw limits its application to low-head sites where head is between 1m and c.10m (though it would be possible to interlink multiple screws to descend a longer slope).

The screw is a physically larger device than its competitors for achieving the same power. The screw diameter, and the cross-section (width and depth) of the intake and outflow channels, sluice gate, and intake screen, are dictated by the design flow. The screw is installed at a technically-optimum standard inclination of 22 degrees from horizontal, and spans the vertical head between the upper and lower water levels. Therefore the screw's length is derived from the head (by trigonometry: head height divided by sine of the angle). The angle may be varied slightly by design.

This large size has benefits, in that the water passing through it is both open to air and constrained only in fairly large and slowly-rotating subsections of the device. This means that the screw can both convey large debris without damage and can reliably convey fish unharmed through its full length. Therefore no fine screening is required and coarse screening alone is acceptable, which minimises the extent to which screening obstructs the flow and reduces the system's output.

While its closest technical competitor the Kaplan may offer a better textbook efficiency before screening requirements are imposed, the screw's performance after screening and its passability to fish mean that it is often preferred to the Kaplan at sites where either might be viable. Overall "water to wire" efficiency of a screw installation (see equation, sec.2 above) is typically between 75%- 80%.

The screw cannot convey fish upstream. Scheme design can often improve upon existing upstream passage for fish, with a well-designed fish pass serving to mitigate local reduction of higher flows.

In terms of susceptibility to flood events, the in-river equipment (screw, sluice gate) is designed for submersion. The gearbox and generator must extend outward from the top end of the screw. It is possible to increase the length of the screw core such that a greater elevation is obtained, or to mount the gearbox at an angle to align the generator perpendicular to the screw. Such expedients allow flexibility in siting the equipment above expected flood levels. However other electrical equipment including the control system can be positioned elsewhere prudently for flood conditions.

6. Historical context of the exploitation of hydropower sites

The history of UK hydropower development is broadly as follows. From Roman times to the Edwardian era, dams and weirs were created at more than 25000 locations around the UK, creating heads of water to provide motive power to mills. While commonly operated to grind grain, watermills were also commonly used for cloth- and metalworking and supported the wider Industrial Revolution until coal became prevalent. Latterly some such mills began to replace their traditional waterwheels with more modern turbine devices for turning the machinery.

From the 1880s, great houses and other individual properties began to install hydroelectric schemes with a turbine turning a generator. This small-scale development grew until economic and regulatory changes in the 1960s caused decline. Meanwhile large-scale development of hydroelectric power in Scotland and Wales began to provide a significant contribution to the UK's electricity supply. Small-scale development began to pick up again with early adopters in the 1980s and has accelerated under incentivisation since 2000.

The larger-scale opportunities for hydropower in the UK involved the construction of dams principally in the mountainous uplands of Scotland and Wales to create high-head schemes. The creation of dams has since become environmentally contentious, to the extent that recent governments have considered that such projects are unlikely to feature in future development of the UK resource. These large schemes - using both a high head and large flow to produce large output – exist therefore in a limited and stable number.

Current development tends therefore to focus instead on run-of-river hydropower. In parts of Scotland and Wales, run-of-river still often involves high-head sites, but elsewhere the majority of new schemes are low-head. This marks a return towards the principles involved in early milling, and therefore favours the redevelopment of many of those existing weirs originally created for watermills. All new schemes must meet various tests to demonstrate their sustainability. Recently, regulators have also shown an interest in identifying potential sites, with a view to making strategic judgements at catchment level on the priority or desirability of development. Such intervention is a new departure, and implies a new challenge to landowners' aspirations for their individual sites.

As in their earlier use, low-head sites offer a modest output in a decentralised location in the community. This decentralisation was originally the product of technical limitation, but such localised generation now has new merit in planning to reduce grid burden and reliance on fossil-fuel sources.

7. Layout of the scheme presently proposed

Please refer to Design & Access Statement for specifics of how the above principles are applied in the layout of the present scheme.

In essence, the scheme in all its elements constitutes an exception to non-development in the flood plain, as it is inherently water-compatible development whose location is essential to its operation.