Aquila Capital

TECHNICAL CHARACTERISTICS OF A HYDROPOWER PLANT

UNDERSTANDING THE MECHANISM OF AN EFFICIENT PLANT

Executive summary

- Hydropower plants capture the energy that flowing water creates and turn this into electricity for end users. The plants can range in size, but take the form of either a run-of-river plant, pumped-storage power plant, or a reservoir plant.
- Hydropower is a very economically viable technology in terms of maintenance and operation costs and a long service life, and also has among the best conversion efficiencies of all energy sources.
- Hydropower plants are typically built from the same components, but each one is always custom-designed to match the needs of a specific project, particularly with respect to available head and flow. Therefore, a number of factors need to be considered before constructing a plant. This includes finding a suitable site (which can impact the future production of the plant), picking the ideal turbine to use, and selecting the most suitable type of plant to build according to the project's needs.

Authors:

Tor Syverud, PhD
Head of Investment Management, Hydropower
tor.syverud@aquila-capital.com

Rachel Ascoli
Investment Associate, Hydropower
rachel.ascoli@aquila-capital.com

1. Introduction

Hydropower plants capture the energy of flowing water and use it to generate electricity. They have been used to generate electricity in Europe since the late 19th century, making hydropower the first renewable energy source to produce electric power in the world. Hydropower plants range in size from micro, which power only a few homes, to giant dams that can provide electricity for millions of people. There are different types of plants – including run-of-river, pumped storage and reservoir – and each plant is always custom-designed to site-specific projects.

This paper explains the technical characteristics of a hydropower plant, including the differences in the types of plants and the components that make them up. It aims to provide in-depth detail on how hydropower plants offer extremely low operating costs and long operating lifespans. The paper also intends to provide an overview of the factors that need to be considered before constructing a plant, from picking the right location to build, to determining the most suitable turbine to use.

How does water turn into electricity?
Bernoulli's equation states that energy is conserved from one state to another. Energy is conserved as the sum of either pressure, kinetic or potential energy.

Bernoulli's Equation

$$\frac{p_1}{pg} + \frac{v_1^2}{2g} + z_1 = \frac{p_2}{pg} + \frac{v_2^2}{2g} + z_2$$

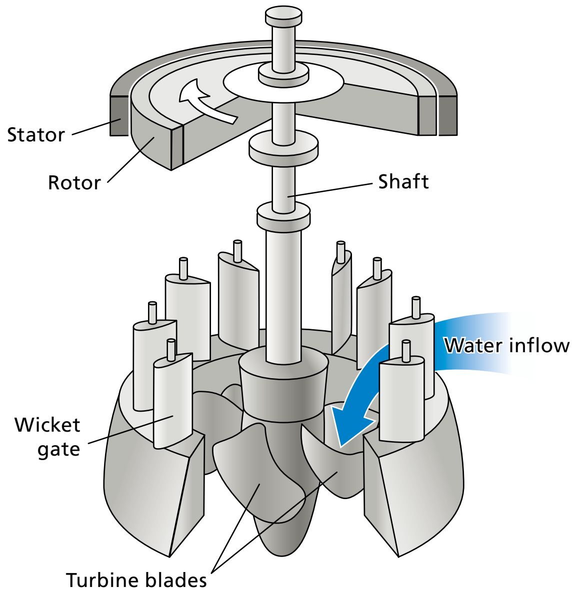
In regard to hydropower, firstly the potential energy needs to be converted into pressure energy, and then kinetic energy, as the water flows through the turbine. The turbine then converts the pressure and kinetic energy into mechanical energy.

The generator finally converts the mechanical energy into electrical energy that the end consumer can use.

2. Technological background

Hydropower plants have always operated according to the same fundamental principle – they capture the energy of flowing water and use this to generate electricity. Water in the hydropower plant flows over the turbine runners whose movement drives the generator. The generator in turn converts kinetic energy into electricity by contact-free induction.

Figure 1: Illustration of a hydroelectric turbine



Source: Aquila Capital. Illustrative example based on a Kaplan turbine.

Usually, there is very low wear on the turbines, and little or no wear on generators, which means the average service life of the electromechanical equipment is between 60 and 80 years.[1] This is far longer than the lifetime of other types of power-generating equipment. The efficiency gains from improved materials and design tools over the past 100 years have amounted to only a few percent and efficiency is now near the theoretical upper limit of 100%, with turbines already reaching 95% efficiency and generators often exceeding 98% efficiency.[2]

[1] *Renewable Energy Technologies: Cost Analysis Series by IRENA. 2012.*
[2] *www.worldenergy.org/data/resources/resource/hydropower. 2019.*

3. Efficiency of hydropower plants

In addition to being a very economically viable technology in terms of maintenance and operation costs and a long service life, hydropower has among the best conversion efficiencies of all energy sources. Energy flows are concentrated and can be controlled. Meanwhile the conversion process captures kinetic energy and turns it directly into electric energy, with little or no losses through heat or inefficient processes. The total conversion efficiency of a hydropower plant typically ranges between 90 – 95%.[3] (Efficiency of wind: approx. 45%, efficiency of solar: approx. 25%).[4]

On average, a hydropower plant generates between three and five gigawatt-hours of electricity per megawatt of installed capacity per year, which is around two to three times as much as a solar pv system. Hydropower also exhibits the highest peak load hours within the renewable energy subset, which indicates the degree of utilisation of a power plant.[5]

4. Constructing a new hydropower plant: what to consider

There are three main types of plants – typically built from the same components – but each one is always custom-designed to match the needs of a particular project. Therefore, a number of factors need to be considered before constructing a hydropower plant.

4.1 Picking the optimal location

Finding the ideal location to build a hydropower plant is crucial. Beyond just constructing a dam, there are a number of factors at play which can impact the future production of a power plant:

Potential production of plant = precipitation x head x catchment area x gravity

- Firstly, to find a good site, Aquila Capital uses hydrology studies of historical river flow data or precipitation to predict the overall water flow at the point of intake of the hydropower plant. This is one of the key aspects that allows us to calculate the future production of the plant.
- It is also important to measure the head, which refers to the vertical fall of the water from the dam to the power station.
- The catchment area is defined as the surrounding area around a river, which will eventually feed into that river. In other words, it is the nearby soil that will absorb water when it rains and that will eventually seep into the river. It is important to consider this because all the water in the catchment area of the river will eventually make its way to the powerplant and allow it to generate electricity. When determining the potential precipitation of a catchment area, it is important to take into account data from representative hydrology measuring stations in the area, determine average precipitation and distribution over the year, simulate historical and future power production, assess vulnerability with respect to floods, and understand the impact of recent and future climate change.

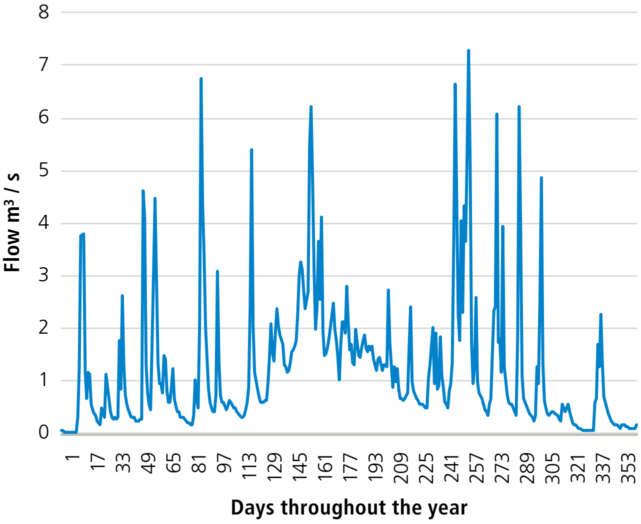
Once the catchment area and water flow are determined, Aquila Capital takes into account the key characteristics of hydropower plants in the area, in relation to the proposed project. This helps us to best calculate potential levels of production. Finding the optimal trade-off between a large precipitation area and a highest possible head is the key to a successful plant.

[3] *www.worldenergy.org/data/resources/resource/hydropower. 2019.*
[4] *Source: https://www.sciencedaily.com/releases/2018/11/181109122623.htm*
[5] *Renewable Energies Agency: Evolution of peak load hours of power plants in Germany, Source: http://bit.ly/1kDwde4*

Understanding water flow patterns

The next step is to measure and analyse water flow levels at the potential power plant location. This data is then sorted to determine the highest and lowest levels of water flow and plotted on a duration curve, which helps to understand flow patterns in terms of percentage of average flow in a year. For example, in Norway, data shows that the heaviest flow of water occurs towards the middle of the year as snow melts in combination with rain (Figure 2).

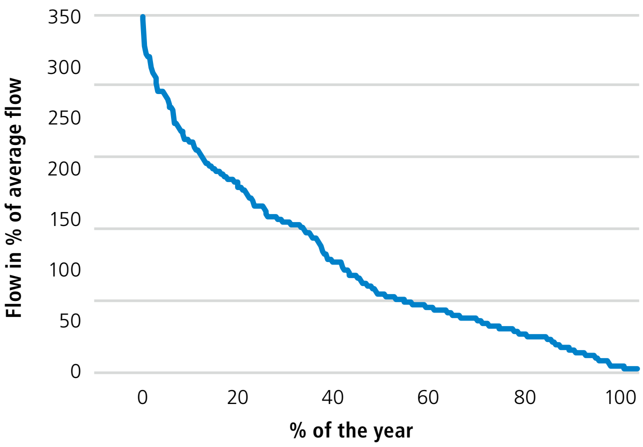
Figure 2: Example of water flow in Norway throughout the year



Source: Aquila Capital

Understanding and analysing the duration curve allows us to determine what type of turbine is optimal for the proposed hydropower plant. Figure 3 highlights that 10% of the year, water flow levels are higher than 250% of the average water flow during the year.

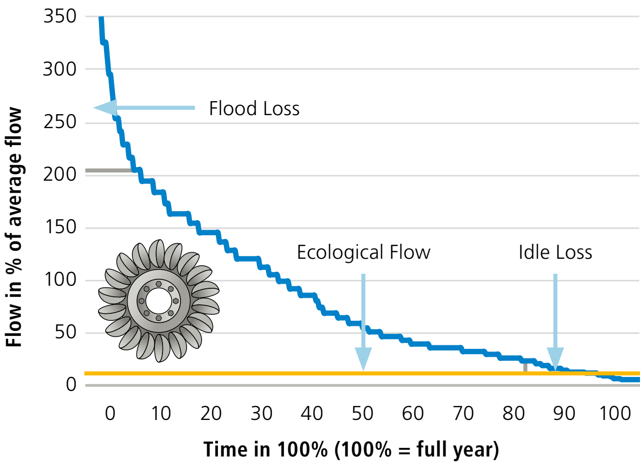
Figure 3: Duration curve of water flow example



Source: Aquila Capital

Water flow that is between 200% and 250% of the average yearly flow is considered flood loss, as it would not be economical to build a hydropower plant that can capture 100% of the water flow during peak times. That would entail building a larger dam, increasing capital expenditure costs, while turbine efficiency is not designed for large variations in water. For most run-of-river plants, only 60–70% of the water is captured for electricity production. The remaining 30–40% is loss in flood, idle losses or ecological flow (Figure 4).

Figure 4: Duration curve example showing flood loss



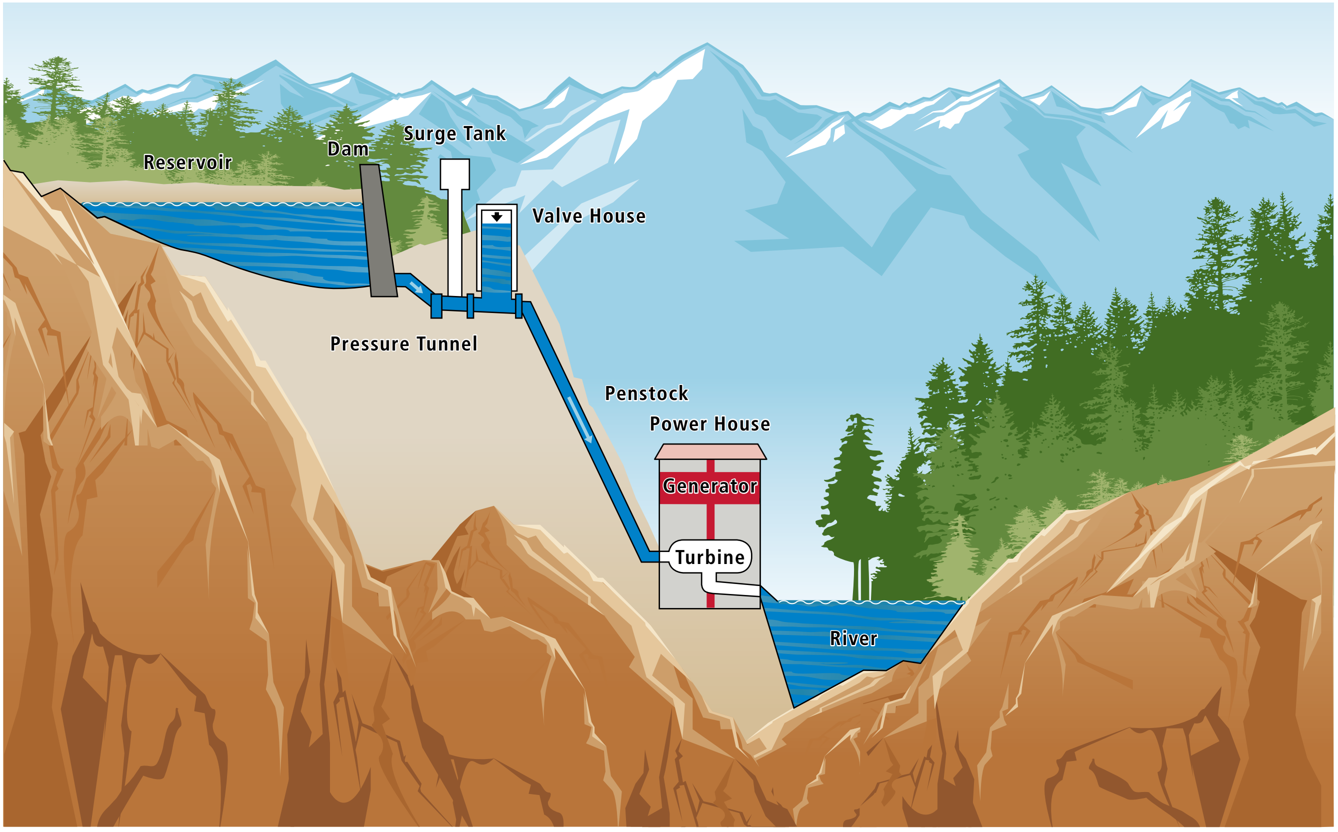
Source: Aquila Capital

4.2 Determining the right turbine

In order to determine the optimal turbine to use, it is important to understand the characteristics of the potential hydropower plant, for example the head and potential water flow of the duration curve. This will help to select the best turbine to match the specific required characteristics. There are three main types of turbines: the Kaplan, the Francis, and the Pelton.

- **Kaplan turbine:** this is used for small heads up to around 30 metres. The Kaplan turbine is suitable for large amounts of water and is formed like a ship propeller with two to six blades. In addition to adjusting the wicked gates, the propeller blades themselves may also be adjusted in order to achieve better efficiencies at varying loads.
- **Francis turbine:** this is used for a low to medium head, ranging from 30 to 800 metres. The water enters the turbine radially and leaves axially. Wicked gates adjust the 'attack angle' of the water to accommodate for various water flows. The Francis turbine can achieve very high efficiencies compared to other turbines, but it also quickly loses efficiency at lower loads. The minimum operational load is typically 25% of the maximum load.
- **Pelton turbine**: this has a high efficiency over a wide range of loads and is particularly useful for high heads and smaller water flows. Water enters the turbine through nozzles. Pelton turbines can be equipped with anywhere from one to six nozzles.

Figure 5: Head and water flow determine the optimal turbine



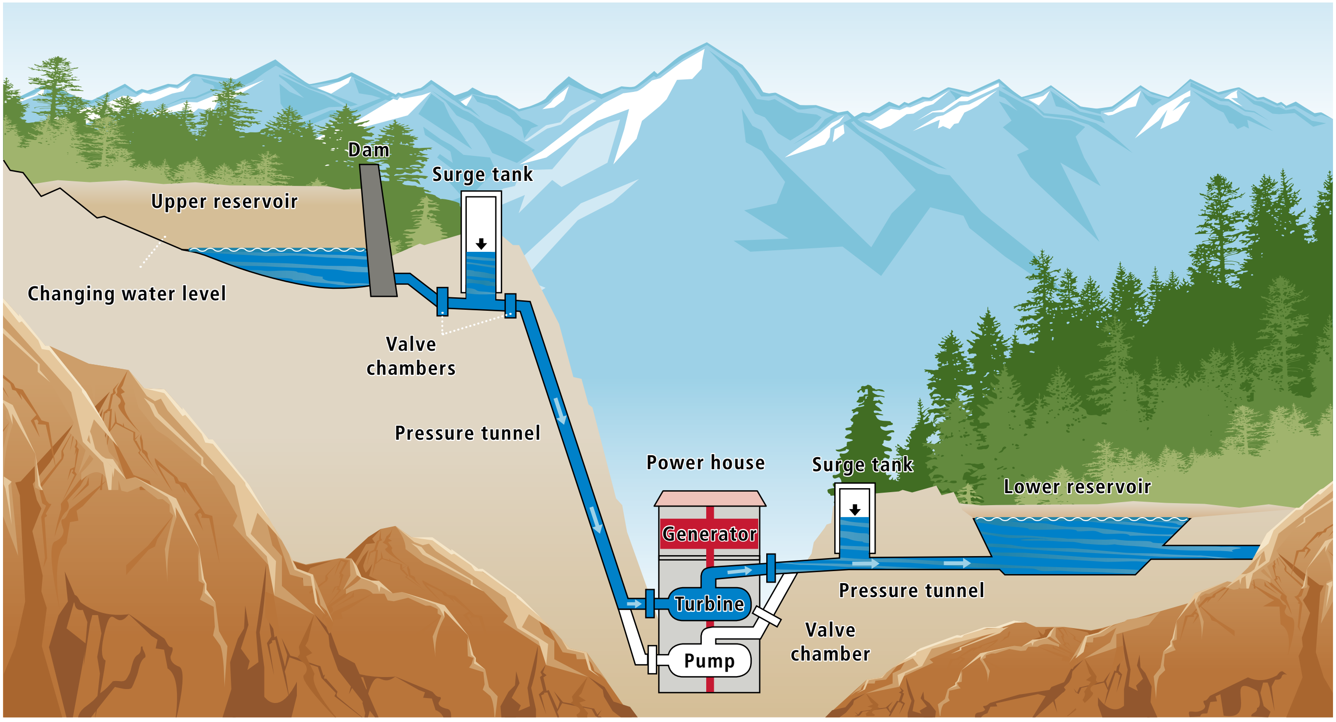
It is also important to take into account the flexibility required regarding the various rates of flow in a typical run-of river plant. A Pelton turbine is highly flexible over a range of water flows. Therefore, if there is a highly variable water flow throughout the year, it would often be best to use a Pelton turbine.

4.3 Types of hydropower plants

There are three main types of hydropower plants: run-of-river, reservoir (stored hydro) and pumped storage.

- **Run-of-river plants:** these tend to be built on running streams and consist of a weir, which provides a controlled damming of the water and guides the flow to a turbine generator. Beyond this however, they have little to no effect on the water level behind the dam. They are compact in construction and generally blend into the landscape.
- **Reservoir plants:** these plants function in a similar way to pumped storage power plants, but are often connected to a lake that is filled by flowing water, such as a river. The water is retained by a dam and powers the hydropower plant's turbines via large pressure pipes. The turbines are not designed for uninterrupted operation however, as the flowing water tends to supply less water than the plant is capable of processing. This type of plant is therefore used to smooth peaks in energy demand.
- **Pumped-storage power plants:** these plants, by contrast, tend to be filled with artificial water flows and not by a natural inflow such as a river. The water volume required for operation is pumped up from a basin at a lower level. Because of the quantities of energy required to pump water to the upper basin, this type of hydropower plant is mainly used for energy storage. When energy demand is low, the upper reservoir can be filled for later use when demand is higher.

Figure 6: Typical pump-storage plant



Source: Aquila Capital

4.4 Components of a hydropower plant

The components of hydropower plants are largely the same regardless of the type of plant. Stored and pumped-storage plants have differences in their dams to ensure storage capacity, and pumped storage plants have further mechanisms installed in their power houses to allow the plant to pump water back up to the top reservoir.

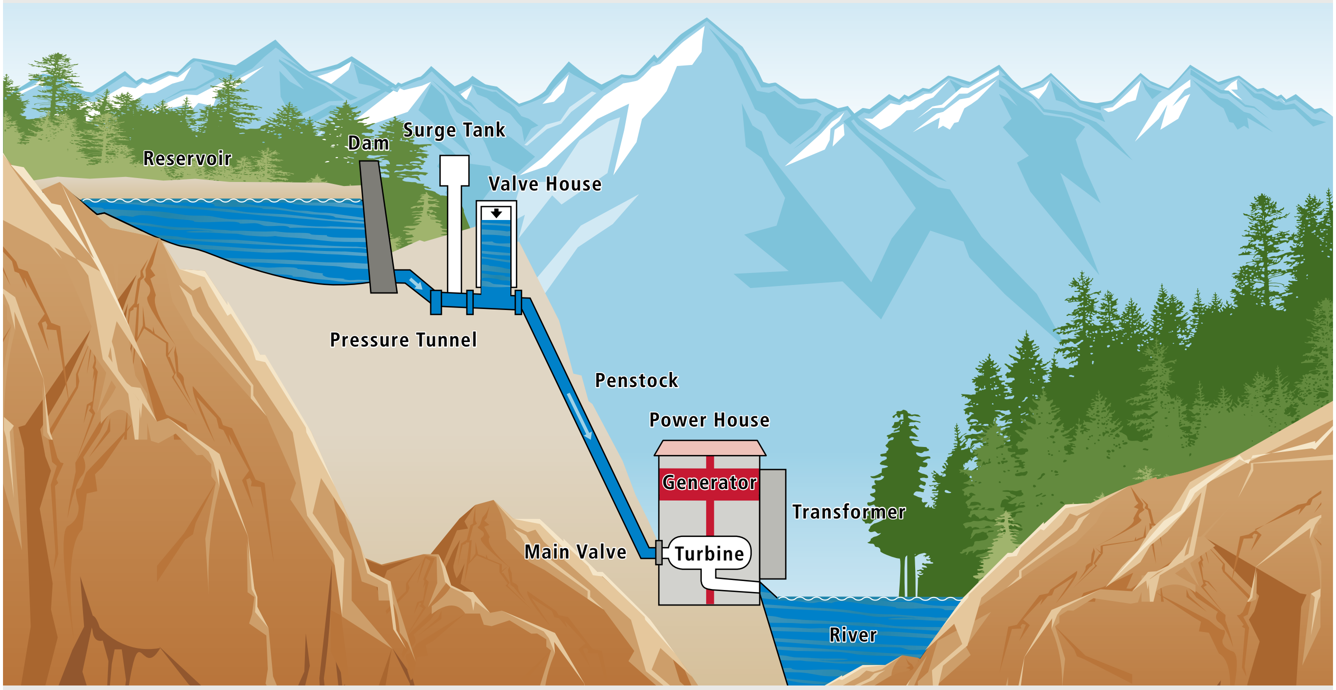
The building blocks of a hydropower plant typically include a dam, intake with trash rack and gates, pipeline or tunnel, main valve, turbine and generator, transformer, trail race pipe and grid connector (Figure 7).

Figure 7: A typical hydropower plant

Dam: At the very top of the hydropower plant, the dam is designed to stop the water in the river or lake outlet, and lead it to the intake with trash rack and gates (Figure 8). In a run-of-river plant, the dam does not have the capacity to withhold water for storage, it merely acts to guide the water. However, in pumped or stored hydro plants, the dam acts as the storage mechanism. The water is then lead through a trash rack and gates to ensure that as much debris as possible from the river is blocked from flowing into the turbine.

Pressure Tunnel: The water then flows into a pipe or tunnel which leads it along the river and transports it to the powerhouse (Figure 9). As the water flows downhill through the pipe or tunnel, it builds up pressure and gathers pace.

Main Valve: At the entrance of the powerhouse is a main valve which is designed to close automatically (and without the use of external power) in case of a failure The main valve is designed to stop the water automatically in case the turbine was to shut down either unexpectedly or on purpose by the operator.



Turbine: Once the water flows through the main valve, it flows further into the turbine with the generator (Figure 10). The water drives the turbine wheel or runner, which is connected to the generator. The generator then converts the mechanical energy from the turbine into electricity.

Generator: The generator is connected to the grid via the transformer and switch gear enabling the safe connection to the grid, thus allowing the electricity generated to reach end consumers.

Transformer: The electricity generated passes through a transformer where the voltage is altered to match that of the grid. The generator is controlled by the control units which allow the operator to essentially turn the plant on and off and connect it to the grid (Figure 11). The control units also control how much water is flowing into the intake valve, at what level the generators are operating, and controlling the pressure within the whole operation.

River: The water that flowed through the turbine is sent out of the hydropower plant via the tail race pipe or channel, and re-enters the river (Figure 12).

Figure 8: An arc dam at Aquila Capital's Holmen power plant

Source: Aquila Capital

Figure 9: Piping leading to the power plant

Source: Aquila Capital

Figure 10: A generator being installed on a turbine

Source: Aquila Capital

Figure 11: Example of a control room

Source: Aquila Capital

Figure 12: Example of the tail race channel leading water out of the power plant

Source: Aquila Capital

5. Aquila Capital's expertise in hydropower

Aquila Capital's dedicated hydro team has been set-up in 2008. Since then, the team has acquired numerous plants across Norway, Portugal and Turkey. Aquila Capital has 143 hydropower plants with a production capability of around 2 TWh annually, based on a transaction volume of EUR 1.1 billion as of end 2018.

In addition to being an efficient and low-cost technology, hydropower plants offer other benefits – they can be remotely controlled from the operational headquarters or even operate automatically on a stand-alone basis. This means that the operational headquarters can be located several hours drive away from the plants, as the plants do not need to be manned continuously.

In remote locations, Aquila Capital usually employs a local farmer which after some training is fully able to look after the plant and conduct regular check-ups. When more critical problems arise, a higher skill level technician is dispatched to visit the power plant. Also, as the high voltage transformer and switch gear is kept in a separate, locked room, this allows anyone without special high voltage electricity training to enter the plant after some basic training only. Only employees that are trained specialists in high voltage applications are dispatched to the hydropower plants if a problem arises with the high voltage systems. The advantage of this competence layer approach is a dramatic cut in the costs of maintenance and operations compared to a more conventional operational setup.

6. Conclusion

Hydropower is a low-cost, mature technology, which benefits from a long service life and high conversion efficiency in comparison to other energy sources. While there are three main types of plants – typically built from the same components – each one is always custom-designed to match the needs of a particular project. Therefore, a number of factors are considered before constructing a hydropower plant. This includes finding the right catchment area and water flow to determine the optimal location for construction, to selecting a suitable turbine to match the specific required characteristics of the project.

Aquila Capital has several years of experience in hydropower and benefits from a dedicated hydropower team. Our technical expertise in the sector, in addition to our strong network, enable us to take the extra step, from carrying out sufficient due diligence before constructing a plant, to keeping maintenance costs low throughout a project.

Table 1: Comparison of renewable energy systems

	Photovoltaics	**Wind power**	**Hydropower**
Feed-in remuneration	Yes	Yes	Rarely
Concession duration	Up to 20 years	Up to 20 years	50 years to perpetuity
Base load capacity	No	No	Yes*
Residual value	Very low	Low	Generally higher than purchase price
Correlation with other renewable energies	Low	Low	Low
Market price risk	No	Low	High**
Debt financing (average)	60–75%	50–65%	Approx. 50%
Inflation protection through price of electricity	No	Low	High
In industrial use for	Approx. 15 years	Approx. 20 years	Approx. 120 years
Expected return (IRR)	6–7% p.a.	5–8% p.a.	6–9% p.a.

The above is an illustrative representation of core markets in Europe. Details may vary.
** Particularly reservoir power plants and pumped-storage power plants. ** In the absence of power purchase agreements.*

Source: Aquila Capital Investmentgesellschaft mbH

Watch our video – click below

For more information please contact:

Aquila Group
Valentinskamp 70
20355 Hamburg
Germany
Tel.: +49 (0)40 87 50 50-199
E-mail: info@aquila-capital.com
Web: www.aquila-capital.com

Follow us on

Hamburg · Frankfurt · London · Luxembourg · Madrid · Oslo · Zurich · Invercargill · Singapore · Tokyo

A publication of Aquila Capital Investmentgesellschaft mbH. As of May 2019. Authors: Tor Syverud, PhD, Rachel Ascoli