# Waterwheels to Turbines

## How rivalry between France and England laid the foundations for the modern hydropower industry.

Hydropower provides nearly one-fifth of the world's electricity. Until the start of nineteenth century man's principal source of energy was waterpower, provided by slowly rotating, open millwheels that were inefficient and seldom capable of producing more than 0.5 HP. In contrast, the modern high-speed water turbine coupled to an 800 MW generator is capable of producing over one million horsepower. This remarkable transformation can be traced back to the rivalry between France and England in the nineteenth century, a story that incidentally provides a fascinating insight into the origins of our respective engineering professions.

At the time the world was going through a period of unprecedented change as a result of the industrial revolution, which started when enterprising textile manufacturers harnessed the rivers of northern England to drive looms. It eventually transformed society by shifting the balance of power from the landowners to the new industrialist class, and by doing so it changed the world for ever.

At the time a nation's wealth lay in its ability to produce iron in large quantities. It would be no exaggeration to say that the industrial revolution was built on iron, because it was needed in almost every aspect of the industrial process - for the machines that manufactured the goods that were traded across the world on iron railways and in ships increasingly built of iron. And in a century that included the Napoleonic and Crimea wars, and countless colonial skirmishes, iron was needed for the growing armies of the newly industrialised powers in an increasingly unstable world.

The inexhaustible hunger for iron posed a serious economic and strategic challenge to aspiring nations, because any country that failed to keep up in its production simply fell behind in global influence and wealth. The stakes were especially high in Europe which was entering a period of intense national rivalry.

The main challenge arose from the fact that the production of iron is an energy-intensive process, and at the time the only practicable sources of energy were rudimentary steam engines or inefficient waterwheels. Energy demand soared as nations struggled to compete. In the early 1800s a typical blast furnace using charcoal required 2-4 HP to drive the blowers, whereas a few decades these were replaced by coke furnaces needing 200 HP, and later 2,000 HP.

The scramble for energy particularly affected France which, unlike its rival across the Channel, had few coal resources and was therefore forced to rely heavily on waterpower. However, all the obvious mill sites in the country had already been taken, to the extent that it was said one could travel from one end of France to the other without being out of sight of a waterwheel. Faced with the need to extract the maximum energy from its overtaxed rivers, the French government and various scientific bodies offered generous prizes to designers of more efficient "water motors".

It was against this background that, in the early years of the nineteenth century, several Frenchmen intellectuals emerged to take the science of waterwheel design forward into the age of the turbine.

### The French pioneers

The idea of applying scientific principles to practical ends attracted people from many walks of life and across a wide social spectrum. In France they tended to come from universities or the military, whereas in the Anglo-Saxon world they were often millwrights and craftsmen. From such wide-ranging backgrounds the forerunners of the modern engineering profession emerged.

The first of the Frenchmen was Jean-Victor Poncelet, better known as one of the founders of projective geometry. He had been an officer in Napoleon's army before becoming Professor of Mechanics at Metz University. Poncelet succeeded in doubling the efficiency of waterwheels by curving the paddles to reduce turbulent losses. His designs were initially very popular but they were never going to provide the uplift that the French Government so desperately needed, and by 1850 they were discarded in favour of other machines developed by two more of his countrymen, Claude Burdin and Benoit Fourneyron, both mathematicians from the prestigious Ecole des Mines.

Burdin's work was mainly theoretical and focussed on hydrodynamic principles, but he recognised the importance of the speed of rotation of the wheel and first coined the word 'turbine', from the Latin word 'turbo' meaning to turn or spin. At this stage it must be remembered the starting point was still the slow-moving open water wheel that until the changes introduced by Poncelet had remained largely unchanged for millennia.

Burdin reasoned that a jet of water under pressure contained more energy than a free-flowing stream, but it was left to Fourneyron to introduce the novel concept of enclosing the waterwheel in a metal casing and then supplying it by pipes, or 'penstocks', that conveyed water down the hillside from a higher elevation. This caused the flow to enter the turbine under pressure at a far greater velocity than was possible with an open channel, so that the wheel, or 'runner' as it became known, rotated faster and was significantly more powerful.

Fourneyron put this idea into practice by building a turbine capable of produced 50 HP of mechanical power – obviously there was no electricity in those days - while rotating at the still relatively modest speed of 60 rpm, and in 1832 he was duly awarded a coveted prize from the French Academy of Sciences for the 'Design of the most effective Water Engine'. Five years later he repeated the concept by building a mill in the Black Forest, where the turbine produced 60 HP with an efficiency of 75%, rotating at what was then the remarkable speed of 2,300 rpm under a head of 108m.

Due to flow restrictions Fourneyron's machines never exceeded this, but nevertheless the twenty-fold increase in output over the traditional waterwheel was a dramatic leap forward. Furthermore, his concept could be adapted to any topography provided the flow could be tapped off at a high level and transported down the hillside a penstock. Suddenly the old constraints on finding a suitable mill site had been lifted and there was an untapped resource of entirely new sites that could be brought into play to generate more power than had ever been previously contemplated.

While the French pioneers made great advances in uncovering the basic principles of extracting energy from flowing water, there was still a long way to go reach the designs we know today. Much of this work was done in the USA by their English and American counterparts.

**James Francis**

Prominent amongst these was, James Francis, who left school in his early teens and emigrated from England to America in 1833. When he reached the New World, Francis initially secured work dismantling locomotives that had been imported from England, measuring and carefully recording the details of all the parts so that they could be reproduced in the USA.

His talents were obviously recognised early because in 1837, at the age of 22, he succeeded in getting himself appointed as Chief Engineer for the Lowell waterpower system on the Merrimack River in Massachusetts. Lowell were textile manufacturers with some of the largest factories in the country, powered by a series of watermills supplied from a canal system that was started in 1822 and continued to be expanded over many years. In addition to powering the factories, the canals were used to transport the raw materials to the factories and the finished product to the markets, so the success of the whole undertaking depended on the hydraulic system.

At the time Francis was appointed, Lowell had been through a period of rapid expansion that was putting a severe strain on the available water resources. The company simply had not got enough power to sustain the burgeoning business, and clearly something had to be done about if it was to retain its pre-eminent position as the nation's leading textile producer.

Francis tackled the challenge with vigour. He built new reservoirs and clamped down on wastage, but most importantly he embarked on a series of studies to find a more efficient water turbine.

Despite his limited education his approach was based heavily on scientific investigation and analysis. These early experiments laid the foundation for the scientific measurement of water flow. Francis became known, not always affectionately, as the “Chief of the Water Police” for the way in which he assiduously monitored water use by individual factories and penalised those he thought were being profligate with his most vital resource.

In his lifetime Francis received many honours, including election to the prestigious post of President of the American Society of Civil Engineers. But perhaps his greatest legacy is the fact that the Francis turbine is still the most widely used today and his name is known to every hydropower engineer.

**Lester Pelton**

While Francis was working for the textile industry in the East Coast, and altogether more rumbustious industry was establishing its presence two thousand miles away in California, where the gold rush was attracting more than its fair share of adventurers. One of these colourful characters was a young man from Ohio, Lester Pelton, who again with little formal education. When he failed to make a fortune by prospecting for gold, Pelton took a job as a labourer in the mines and later graduated to becoming a millwright looking after the ore crushers. His real interest lay in trying to meet the rapidly increasing demand for power from the mines which required large amount of energy.

While some of the mines harnessed the energy of small mountain streams using crude turbines, most were powered by wood burning steam engines with the result that the mountainsides around were rapidly being denuded of trees. Pelton could see that this was causing serious environmental problems, and he began to look for better ways of extracting more energy from the small streams that flowed down the steep hillsides.

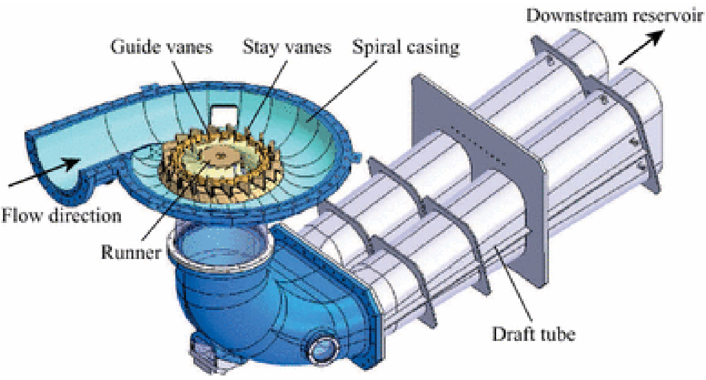
At the time the simple turbine that the miners were using consisted of pipes running down the hillside terminating in a nozzle from which a jet of water was directed onto buckets fixed to the perimeter of a freely rotating wheel. By doing this it was extracting kinetic energy from a jet of water at atmospheric pressure in contrast to the Francis turbine which extracts potential energy from changes in pressure across the runner blades in an enclosed turbine.

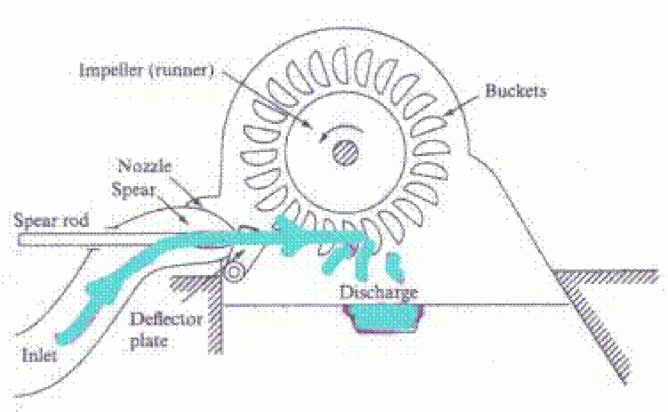
Pelton recognised the key to improving the efficiency of these devices lay in reducing the turbulent losses and he set up a series of experiments to investigate the effect of different designs at the University of California, an ambitious step for a man of his background. By experimenting with the number and positioning of the nozzles, and the shape and spacing of the buckets, he eventually settled on a twin bucket arrangement with a central splitter to eliminate splashback. The result was a huge in-crease in efficiency over the primitive turbines then being used by the miners.

Pelton was so impressed by the performance of his new turbine that he took out a patent but the anticipated rush of orders did not materialise and disappointed with the lack of interest from a world that was too busy making money to realise the importance of using water efficiently, he waited for an opportunity to demonstrate his improved design. Eventually it came in 1883, when the Idaho Mining Company held a competition to decide which turbine they would buy for a planned mine extension. Pelton’s machine won conclusively, reaching an efficiency of over 90% while his three competitors could only achieve between 60% and 76%.

From that time on Pelton never looked back. In 1888 he formed the Pelton Water Wheel Company of San Francisco which expanded production to meet increased demand, and the machine that now bore his name rapidly rose, alongside the Francis turbine, to become one of the mainstays of the hydropower industry.

*Francis Turbine*




*Pelton Turbine*

### *Francis and Pelton Turbines*

*Francis and Pelton turbines perform exactly the same function – extracting energy from a flow of water – but in an entirely different way.*

*Flow in a Francis turbine is enclosed and under pressure, and the runner extracts **potential energy** as it creates a reactive force on the vanes.*

*Flow in a Pelton turbine is at atmospheric pressure once it leaves the nozzle, and the runner extracts **kinetic energy** from the impulse of the jet on the buckets.*

*Hence they are respectively referred to as Reaction or Impulse turbines.*

*Under optimal conditions of head and flow both can reach efficiencies of 95% or more, but this can drop off rapidly as flow conditions change.*

*Average efficiency over the anticipated operating range, together with the associated E&M and civil works costs, are the main factors in the choice of turbine.*

**A long legacy**

Modern water turbines are highly sophisticated machines that are constantly under refinement as performance limits are stretched. There were many other pioneers involved but French intellectuals, urged on by the necessity to compete with Perfidious Albion, played a leading role in developing the early concepts, which were then taken over by their Anglo-American cousins from humbler backgrounds. Together they succeeded in laying the foundations of the modern hydropower industry by optimising the extraction of mechanical energy from flowing water. It would be left to another generation to develop the generators, transformers and transmission lines that convey electric power to millions of consumers around the world today.

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