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FLUID FLOW: PELTON WHEEL

ACEA 6005 Structural & Fluid Analysis

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10th August 2026

Main Body of Research Word Count: 3296

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1. Introduction

This report investigates fluid analysis of the Pelton wheel for energy generation. The report is divided into four sections to provide an evaluation of the application, operation and performance of Pelton wheels. The historical and current applications of Pelton wheels are researched with further consideration of future developments. Material selection, manufacturing and quality assurance processes are discussed to evaluate the efficiency factors.

A laboratory experiment was conducted to determine the characteristics of the Pelton wheel turbine. The results are analysed to provide understanding of the fluid flow behaviour, whilst discussing limitations and improvements. The final tasks investigate the fluid flow behaviour by explaining the experimental results. Industry standards and codes of practice are discussed in Task Four to highlight design and operational compliances.

2. Task One

This section investigates the operation of the Pelton wheels, considering the historical, current and future applications and the technologies. Additionally, materials, manufacturing processes and quality assurance are investigated.

2.1 Hydroelectric Power

Hydroelectric power is produced by converting energy of water from height or fast-flowing sources into mechanical energy. Power from a renewable energy source produces lower emissions than traditional fossil-fuels, lowering environmental impacts, (*Britania 2018*).

According to *Global Electricity (2026)*, hydropower generates 14% of global electricity in 2024, can be generated by different turbines, such as the Pelton wheel; suitable for high-head and low flow conditions. Other turbines include Francis and Kaplan for low head applications.

2.2 Operation of a Pelton Wheel

Pelton wheel is an impulse turbine used to generate hydroelectric power by converting kinetic energy from a water jet to rotational mechanical energy. A nozzle directs high velocity water into buckets around a turbine shaft. The water initially forces the turbine to rotate, catching each bucket and transferring the momentum around the turbine shaft. The impact of water causes small impulses, and momentum carries the motion around the shaft. The turbine shaft is connected to a generator allowing for the kinetic energy to be converted to electricity, (*HAP, 2011*).

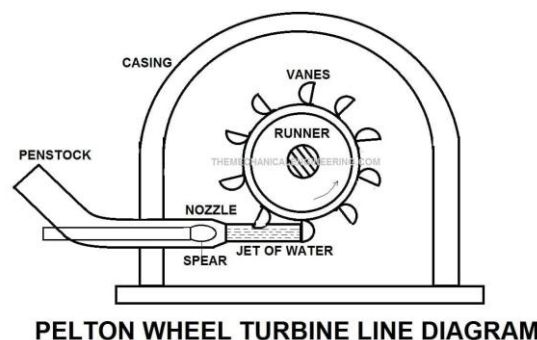


Figure 1 - The Pelton Wheel Diagram (Sudeep, 2018)

When the water strikes the buckets, ideally all energy from the water jet would be transferred to the generator. However, due to friction, turbulence and impact splash, not all energy is transferred. Similarly, the hydraulic efficiency is determined at half of the water jet velocity. At high RPM, momentum cannot transfer effectively, resulting in minimal power output. At low speeds, turbulence is greater resulting in high energy loss. Consequently, the maximum efficiency and is estimated to be half the jet velocity.

2.3 Historical Development of Pelton Wheels

Lester Allan Pelton recognised inefficiencies of the original concept of the water wheel, where most of the kinetic energy was lost. After observing a misaligned water jet, patented in October 1880, Pelton developed the Pelton wheel containing a split bucket design. Pelton understood that increased momentum occurred when the water jet struck the edge of the buckets. The split bucket diverted the water almost 180° with a central splitter, increasing the momentum in the system, resulting in higher energy output. This improved efficiency leading to widespread application in mining industries, (ASME, 2024).

The Pelton wheel was particularly prominent during the California Gold Rush where demands increased, and efficiency and reliability were crucial. For example, the 1000hp Pelton wheel, operated between 1898 and 1937. Now located in the North Star Mining Museum, the 9.1m Pelton wheel used a 243.8m vertical waterfall to power compressed air for the mine, (Laessig, 1019).



Figure 2 -Pelton Wheel Located at North Star Mining Museum (North Star Mine Powerhouse and Pelton Wheel Museum, 2023)

2.4 Current Applications

Pelton wheels generate renewable power, particularly in high-head, low-flow environments. Large elevation in mountainous areas produce high velocity water jets to drive the turbine of the Pelton wheel and are used for remote areas that are not connected to the national grid, such as pico-hydropower systems, (Shrivastava and Rai, 2025).

In modern applications, Computational Fluid Dynamics (CFD) is a numerical modelling technique that simulates how water interacts with the Pelton wheel prior to manufacture. Traditional methods relied on physical prototypes, increasing development time and cost. CFD optimises turbine performance by simulating fluid dynamics, turbulence, boundary layer, momentum and flow separation to optimise design efficiency, (Harpendi et al., 2021).

Modern applications require reliability, durability and efficiency through the use Supervisory Control and Data Acquisition (SCADA) for continuous condition monitoring. SCADA monitors parameters allowing faults to be identified at an early stage and reducing operational breakdowns, (Özgül *et al.*, 2025).

2.5 Future Advancements

For further advancements, reliability, durability and efficiency must increase for continuous growth in use. As shown in Annex 1, hydroelectric power has shown to be the largest power source in renewable power generation. This highlights the global growth of renewable energy and its future demand. It is expected that instead of changing the Pelton wheel concept, future advancements focus on condition monitoring. These developments increase operational performance and longevity by continuously monitoring conditions, allowing early fault detection and reducing operational breakdowns, (Sulaima *et al.*, 2026).

Using Digital Twin technology, a virtual representation is maintained using real-time sensors, communication networks and data-driven intelligence to monitor the system. Future developments include artificial intelligence (AI) and machine learning capabilities to identify abnormalities and optimise performance. AI allow machine learning capabilities to enable further predictive maintenance and component degradation detection. This technology improves reliability and reducing maintenance, human intervention and hazards, (Ersan and Irmak, 2024).

CFD enables engineers to perform increased analysis in how the water jets perform with the Pelton wheel. Advanced CFD will reduce processing time, create complex geometries of components such as the bucket or nozzle, and increase the precision of simulations, reducing prototype requirements.

2.6 Materials

Material selection for a Pelton wheel is critical to maintain durability, reliability and efficiency to prolong operation and performance. As the buckets and runner subjected to high velocity water jets, continuous impact occurs throughout its operation. Therefore, material properties require high tensile and fatigue strength, with corrosion and wear resistance for continuous operation.

Finite Element Analysis (FEA) allows structural behaviour can be assessed under predicted loading conditions for analysis prior to manufacture or prototype development. FEA supports material selection as multiple materials can be analysed by assessing the material's response to the load, enabling engineers optimising material selection or design; reducing manufacturing costs and development time. Figure 3 illustrates an FEA model of a pico-Pelton concept demonstrating displacement under two loading conditions: Force of 11698.87 N and Torque of 636.6 Nm. The FEA model highlights that

the greatest displacement occurs at the outer edge of the bucket where the water is subjected to. This highlights areas susceptible to deformation, demonstrating material selection must have sufficient toughness to withstand applied loading to maintain structural integrity, (Ishola et al., 2019).

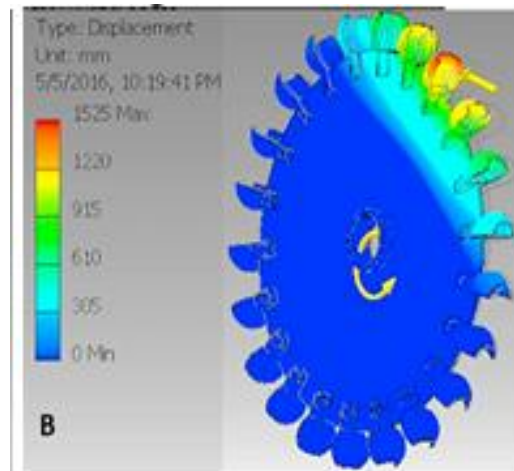


Figure 3 - (Ishola et al., 2019) Pelton Wheel FEA

Annex 2 compares materials using Von Mises, principal stresses, displacement and safety factor. Von Mises is used to assess whether materials can withstand complex loading without yielding. Material selection depends on these factors to maintain the structural integrity on the operation; A390 aluminium alloy was determined suitable due to structural performance, low cost and lightweight properties, (Ishola et al., 2019).

2.7 Manufacturing Processes

Traditionally, Pelton wheels were manufactured by casting due to complex geometries of the bucket. Although casting was susceptible to defects that reduced efficiency and component failure, casting was preferred over traditional machining methods due to complex manufacture of the Pelton bucket geometry. Following casting methods, Computer Numerical Control (CNC) machining methods were used to achieve precise dimensional accuracy and improved surface finishing over casting. This ensures manufacture closely follow design, reducing manufacturing defects, (Simiscasting, 2025).

Annex 3 presents modern manufacturing flow, incorporating Computer Aided design (CAD) with the integration of FEA (shown as FEM) and CFD to produce components through CNC or additive manufacturing (AM). Enabling high accuracy and material selection ensures design materials and manufacture optimising operational performance. AM further supports prototyping by enabling complex geometry from CAD

models that CNC would struggle, reducing development time and material waste, (*Udroiu et al., 2011*).

Following manufacturing, methods are included to improve mechanical properties of the materials used; including heat treatment and corrosion protection. Enabling this helps components withstand continuous impact loading of the water jets.

2.8 Quality

Components undergo quality inspections and testing to verify the product has been manufactured to the design specification. Quality assurance identifies manufacturing or material defects prior to product operation. Two examples of quality assurance are Coordinate Measuring machines (CMM) and Non-Destructive Testing (NDT). These methods allow manufacturers to improve reliability, durability and efficiency of the components prior to installation.

CMM is commonly used to verify dimensions and tolerances for critical components. This verifies bucket and runner geometry to ensure the component fits within the tolerances specified in the design and reducing efficiency losses. Minor discrepancies can significantly operation performance, (*pawan_w. 2025*)

NDT methods are used to identify internal and surface defects, such as voids, cracks and porosity without damaging the component. NDT examines the structural integrity of the material using inspection techniques to detect defects that could lead to fracture and operational failure. This ensures the Pelton wheel components comply with design specifications, improving safety and reliability, (*Baker Hughes, 2026*).

3. Task Two

The turbine characteristics of the Pelton wheel were investigated through a controlled laboratory experiment. The equipment, procedure and results are discussed below, followed by calculations and a critical evaluation of the results. To further analyse, the limitations and potential improvements are discussed.

3.1 Experimental Equipment

The experiment was conducted using the Pelton wheel test apparatus in the laboratory to determine the turbine characteristics. The apparatus consisted of a Pelton wheel impeller, enclosed in a turbine housing, with an inlet nozzle needle to produce the water jet. The nozzle was connected to a manometer that displayed the water pressure set by the nozzle adjuster; at a constant 0.4bar.

At the rear of the apparatus, a belt pulley was connected to two spring balances, by two belts, that were connected to the adjustable braking device. The rotational speed of the belt was measured with a digital laser tachometer. To measure the volumetric flow rate, the water discharged collected into a tank and a stopwatch was used to record the time taken to collect the water.



Figure 4 - Task Two Experiment Set Up of the Pelton Wheel

3.2 Experimental Procedure and Calculations

To begin the experiment, the pump and water supply were switched on, and the pressure was set to 0.4bar, using the nozzle adjustment wheel. The pressure was constant at 0.4bar and confirmed throughout by using the manometer. The water jet struck the Pelton wheel impeller buckets, causing the impeller to rotate. This converted hydraulic energy into rotational mechanical energy.

The Pelton wheel, attached to the turbine shaft, rotated the belt pulley. The rotational speed (RPM) was measured using a digital laser tachometer and recorded. The belt pulley was connected, by belts, to two spring balances and the adjustable braking device. The braking force was increased by 1N increments from 1N to 20N by adjusting the hand wheel, Force Meter 2 and rotational speed was recorded, as shown in Annex 4.

Volumetric flow rate (VFR) was calculated by collecting 10L of discharged water from the Pelton wheel apparatus in the draining tank below and timed using a stopwatch. The water was collected in 17s, resulting in a VFR of 0.588L/s.

Equation 1 – Volumetric Flow Rate

$$\dot{V} = \frac{v_2 - v_1}{\Delta t}$$

$$\dot{V} = \frac{10}{17}$$

$$\dot{V} = 0.588L/s$$

$$\dot{V} = 0.588 \times 60$$

$$\dot{V} = 35.29L/min$$

Using the recorded measurements, the turbine characteristics were calculated:

Equation 2 - The braking force acting on the pulley determined from difference between the spring balance readings.

$$F = F_1 - F_2$$

Equation 3 - The torque on the shaft calculated from the pulley radius (25mm) and the braking force.

$$M = F \frac{D}{2}$$

Equation 4 - The shaft power that the turbine produces calculated from the torque applied and the rotational speed.

$$P_{out} = M \times 2\pi \frac{n}{60}$$

Equation 5 - The hydraulic power supplied by the water was calculated from the hydraulic pressure and the volumetric flow rate.

$$P_{hyd} = \frac{\dot{V} \times P \times 10^5}{1000 \times 60}$$

Equation 6 - The efficiency of the turbine converting hydraulic to rotational energy was calculated from the shaft power to the hydraulic power.

$$\eta = \frac{P_{out}}{P_{hyd}} \times 100$$

3.3 Experiment Results Analysis

Annex 5 presents the results from the experiment, identifying the relationship between rotational speed and shaft power at a constant head of 0.4bar. The hydraulic power remained at 23.527W throughout the experiment, as the volumetric flow rate and the head remained constant. The graph demonstrates the operating characteristics of the Pelton wheel turbine and highlights the change in shaft power under different rotational speeds. The graph visualises the optimum operation loads where the turbine produces the maximum shaft power of 12.566W at 600-640RPM.

Initially, the rotational speed of the pulley was 1185RPM, which was the highest speed of the experiment as the lowest braking force of 0.5N was applied, producing 0.013Nm of shaft torque and 1.551W of shaft power. Despite the high rotational speed, the turbine operated at low efficiency of 6.59% as the low braking force produced low shaft torque. Resulting in minimal conversion of hydraulic energy to mechanical power output, demonstrating that high RPM alone does not correlate to high power output and requires a suitable braking force to convert hydraulic energy to maximum mechanical power output.

As braking force increased, rotational speeds decreased; however, the power and torque on the shaft increased. This establishes that a larger proportion of the hydraulic energy was converted to mechanical power; reaching the maximum of 12.566W at rotational speeds of 600RPM and 640RPM. Annex 5 highlights the optimum operating load of the turbine for maximum power output, achieving 53.413%. The efficiency indicates that 46.587% of the hydraulic energy was lost whilst converting to mechanical power, resulting in larger mechanical system losses such as friction or turbulence. The increase in shaft torque outweighs the reducing the rotational speed, resulting in the maximum power output.

The braking forces continued to increase, further reducing the rotational speed, reducing the turbine to a stop once the optimal operating load had been exceeded. Although the torque continued to increase, the reduction in rotational speed resulted in a decrease in shaft power. This outweighs the increase in torque resulting in the reduced power output. This highlights that the braking load after the optimal operating load prevents the turbine from rotating, and in turn, reducing the conversion of hydraulic energy to mechanical power.

3.4 Experiment Limitations and Improvements

The Pelton wheel experiment identified turbine characteristics; however, several limitations impacted the accuracy and efficiency of results, resulting in impacts to inefficiencies of the turbine to convert hydraulic energy to mechanical power. Addressing these factors, improves reliability for future experiments.

The experiment demonstrated several factors that had potential to cause inaccuracies, firstly in pressure variation. The analogue manometer displayed a constant pressure head of 0.4bar, however, fluctuation may have occurred without being detected. For example, the manometer may have been read at 0.4bar, yet reading was 0.39bar. A digital manometer improves accuracy without ambiguity.

Similarly, the spring balances were analogue, requiring manual readings to calculate the braking force. Due to the movement of the pulley, the Force Meter 2 would vary slightly, resulting in difficulty in taking the measurement. This would influence the shaft torque and shaft power characteristics. If the spring balance had a digital display, the accurate measurement could have been taken without uncertainty.

The maximum efficiency achieved by the experiment was 53.413%, highlighting a significant proportion of hydraulic energy is lost within the system, such as friction or uncalibrated equipment. Friction losses occur due to moving mechanical parts; like, the belts, pulley and turbine shaft bearings. With scheduled inspections, equipment can be maintained, calibrated and lubricated if required. Actioning this, gauges reflect correct readings, and efficiency losses can be reduced.

Repeating the same experiment again to gain an average result would help identify any inconsistencies, increasing the repeatability and reliability in the results. To gain a comprehensive understanding of turbine characteristics within a Pelton wheel, the experiment could be repeated under differing constant pressure heads and volumetric flow rates. This enables further research in how changing hydraulic conditions impact turbine performance when converting hydraulic energy to mechanical power.

4. Task Three

To understand the performance of the Pelton wheel experiment, Task Three evaluates fluid flow behaviour between the water jet and the runner, which rotates the turbine shaft. Fluid flow determines the operational performance where fluid principles (velocity, pressure, momentum, boundary layer development and flow separation) are evaluated to understand the influence on hydraulic efficiency.

4.1 Fluid Flow and Hydraulic Efficiency

Water is supplied to the Pelton Wheel through a penstock before being accelerated through a nozzle to create high-velocity flow. The nozzle converts the water pressure into kinetic energy creating a jet, that is directed towards the splitter of the Pelton bucket. As the water deflects on the bucket, the change in momentum transfers force to the runner, producing rotational energy to the turbine to create mechanical power. Hydraulic efficiency is the measure in how effective the Pelton Wheel transferred hydraulic energy to rotational energy, this is shown in Annex 5. By using CFD, flow behaviour can be visualised and optimised where possible to achieve maximum efficiency, (*Cambridge University Press, 2001*)

4.2 Velocity

The velocity of the water jet is significant when considering the performance of the Pelton Wheel. The high-velocity water jet strikes the bucket, allowing a greater change in momentum and increasing the force to the runner. Bernoulli's equation, *Equation 7*, demonstrates that fluid pressure decreases whilst fluid velocity increases through the nozzle. The continuity equation, *Equation 8*, explains the relationship between the nozzle and water jet as the volumetric flow rate remains constant throughout the experiment, (*Jha, 2020*).

Equation 7 - Bernoulli's Equation

$$P + \frac{1}{2}\rho v^2 + \rho gh = \text{constant}$$

Equation 8 - Continuity Equation for Water

$$A_1V_1 = A_2V_2$$

However, Equation 7 and Equation 8 display theoretical velocity in ideal systems. Energy losses occur through friction and turbulence. Velocity of the water jet can be analysed to minimise losses to increase hydraulic efficiencies with CFD.

4.3 Pressure

The pressure of the water is significant when considering the performance of the Pelton Wheel. Whether the water is stored at high elevation, as such in mountainous areas, or is forced through a nozzle, high pressure is converted into kinetic energy to produce high velocity water jet. This relationship is described in Equation 7 where the reduction in fluid pressure increases velocity.

The buckets operate at atmospheric pressure where energy is transferred through the impact of the water jet on the bucket, rather than the pressure directly acting on the runner. CFD is used to optimise the system, reducing pressure losses to improve the overall efficiency.

4.4 Boundary Layer and Flow Separation

A boundary layer forms when fluids flow around an object from stagnation, at the buckets edge to free flowing around the bucket. Flow separation occurs when the boundary layer loses momentum, causing it to detach from the object. By using CFD, the boundary layer can be visible, shown in Figure 5. The figure shows the higher velocity at the exit of the nozzle, before striking the bucket. As the water strikes the bucket, velocity decreased as energy is transferred to the runner, (Ahmed Al Makky, 2012).

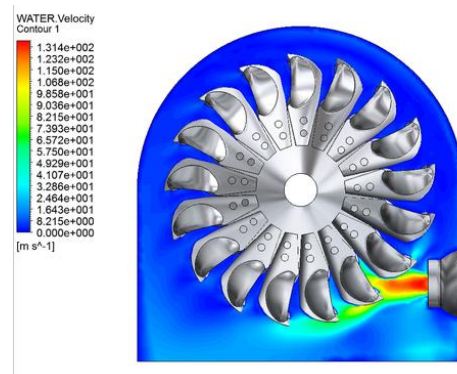


Figure 5- CFD of the Pelton Wheel to Display the Boundary Layer and Flow Separation, (Ahmed Al Makky, 2012).

For efficient systems, smooth surfaces allow the boundary layer to attach to the component. However, roughness, caused by corrosion or defects, creates turbulence in the boundary layer, thickening the layer and increasing probability of flow separation. This causes energy loss as velocity is decreased, as shown in gradient from red to blue in Figure 5, (L. Hector Juarez, 2012)

4.5 Momentum

Momentum is fundamental characteristic for the Pelton wheel. The water jet strikes the bucket producing a change in momentum on the bucket that generates the force of the runner to rotate and convert hydraulic to mechanical energy. The larger the force acting on the buckets, the larger the momentum, producing larger shaft torque (Equation 9).

Equation 9 - Momentum Equation.

$$F = \dot{M}(v_{in} - V_{out})$$

CFD identifies factors that prevent the water from transferring energy to the buckets, reducing the momentum transfer. This includes misalignment of water or material defects like corrosion, (*Science Insights*, 2026).

5. Task Four

Pelton wheels are subjected to codes of practices and industry standards for the design, manufacture, testing and operation stages. These practices increase the safety and reliability of operation and reduce mechanical failure. Table 1 investigates compliance standards of the Pelton wheel.

Table 1 - Codes of Practice and Industry Standards

Codes of Practice/ Industry Standard	Description
IEC 63461:2024	• Step-by-step instructions for testing, ensuring consistency and accuracy. • Maintenance and quality assurance guides • Ensures Designs meet performance standards (European Standards, 2024)
IEC 61116:2025	• Guidance for hydroelectric power systems containing impulse or turbine units up to 15MW and 3M diameter. • Installations and quality control. • Contains equipment technical specifications. (ITechStandards, 2026)
EN60609-1:2005	• Provides Measurement and criteria for cavitation pitting on equipment. • Operational tolerances for defects. (European Standards, 2024)
IEC60041	• Processes to construct acceptance tests to verify turbine efficiency. • Guidance for predictive maintenance and increased durability. • Used to identify performance losses due to installation and friction (ITechStandards, 2026)
ISO 9001:2025	• Establishes quality management systems. • Guidance for control and documentation management to enable traceability. • Used to gain process control and corrective actions. (European Standards, 2024)

6. Conclusion

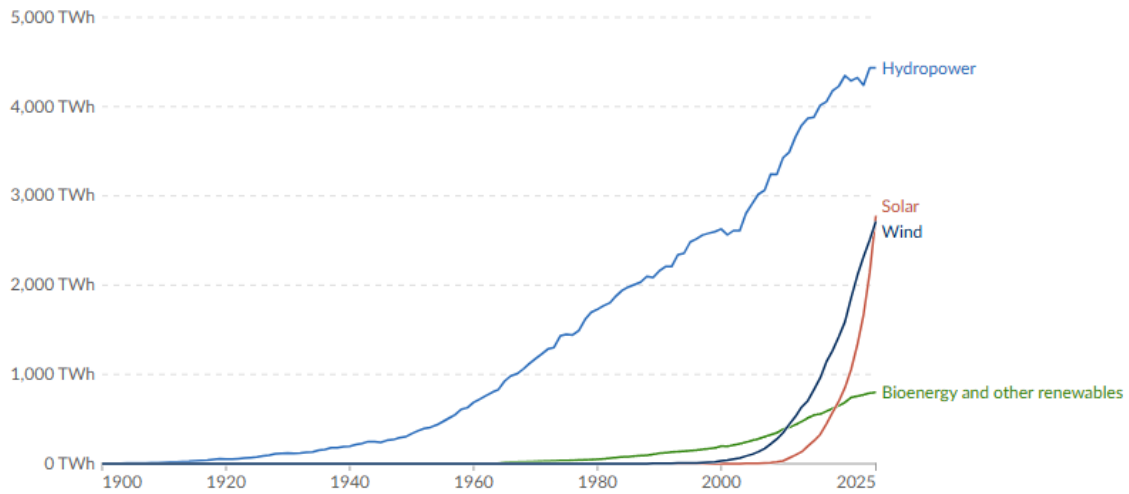
Through secondary research and the laboratory experiment, the application, operation and performance characteristics of a Pelton wheel was investigated. The experiment determined the turbine characteristics through the relationship between hydraulic power and the rotational power output. The results of the experiment aligned with research found in Task One, demonstrating the peak hydraulic efficiency.

The experiment results provided understanding of turbine behaviour, that was further analysed in Task Three, by understanding fluid dynamics characteristics and its effect on the hydraulic efficiency. Task Three also highlighted the importance of momentum transfer and how to minimise efficiency losses. Task 4 discussed the importance to industry standards and codes of practices. Compliance with these standards improves the safety of the design, manufacture, testing and operation of the Pelton Wheel.

Overall, the findings of secondary research and the experiment demonstrate that the Pelton Wheel remains highly efficient and useful, especially in remote applications, supporting hydroelectric power generation in an ever-growing renewable demand. With continued development, found in task one future developments, efficiency can be improved to increase durability, reliability and sustainability.

Appendix

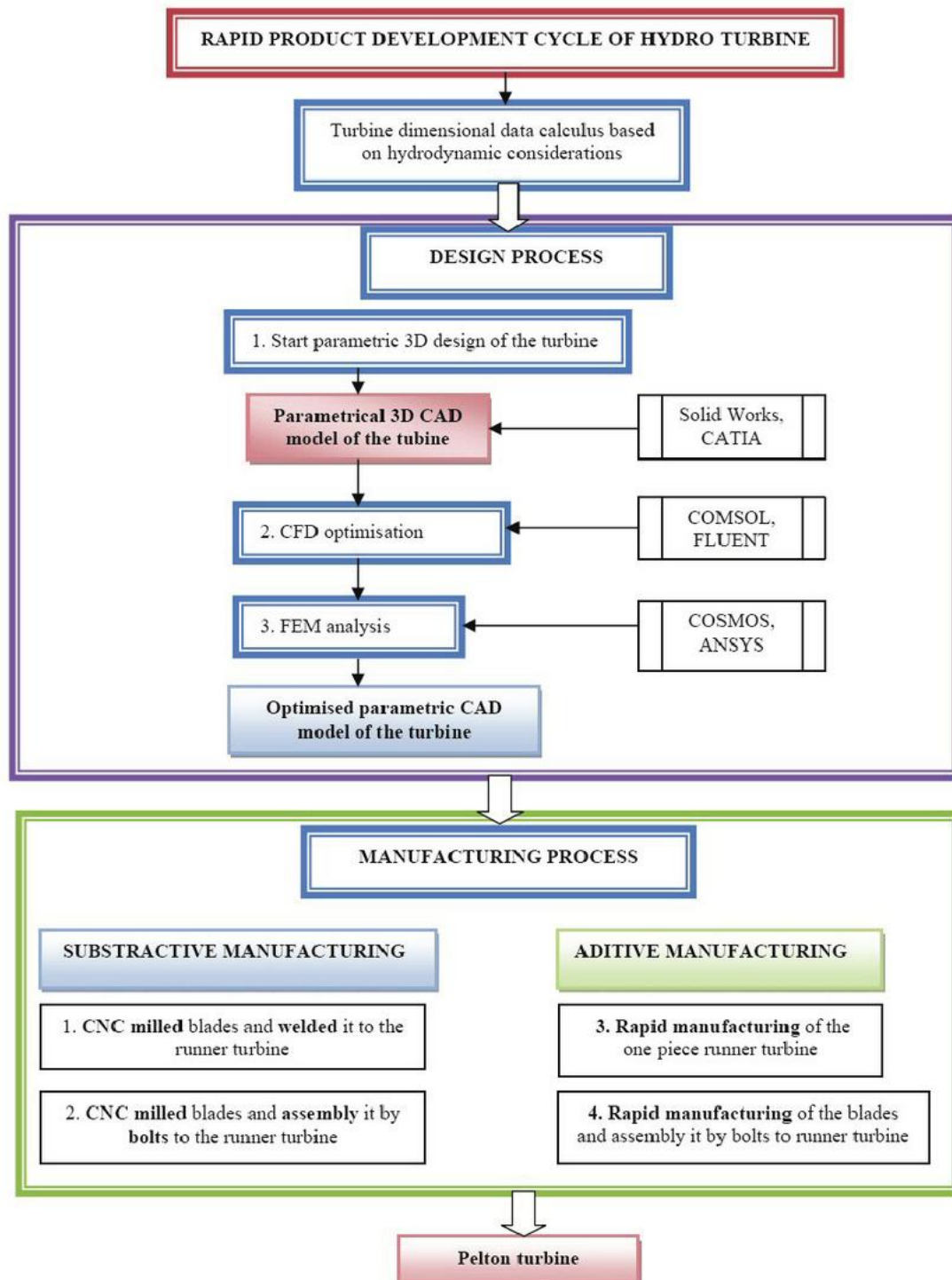
Annex 1: Renewable Electricity Generation by Renewable Source Over Time (*Global Electricity, 2026*)



Annex 2: Material Stress Table FEA (Ishola et al., 2019)

Materials		Steel Alloy	A390 Al Alloy	Plastic
Von Mises Stress (MPa)	Min	0.000102311	0.00135021	0.00226283
	Max	3188.49	1646.82	1864.56
1 st Principal Stress (MPa)	Min	-571.143	-286.612	-496.091
	Max	1825.57	1575.47	1569.39
3 rd Principal Stress (MPa)	Min	-2007.98	-1847.95	-2203.2
	Max	296.708	192.162	393.09
Displacement (mm)	Min	0	0	0
	Max	11.0786	23.0714	1524.52
Safety Factor (ul)	Min	0.0784069	0.166989	0.0536159
	Max	15	15	15

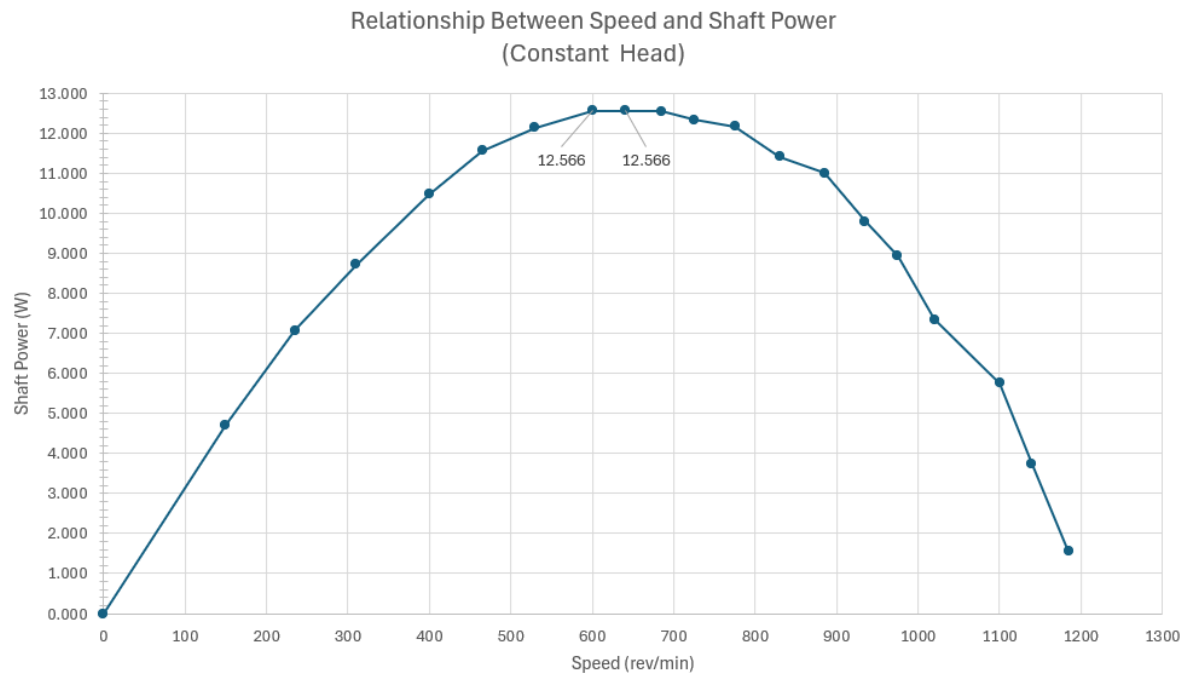
Annex 3: Design and Manufacture Flow Chart of a Pelto Wheel, incorporating CAD, FEA, CNC and AM, (Udroiu et al., 2011).



Annex 4: Task Two Results Table of Pelton Wheel Experiment (UWTSD)

Force meter 1	Force Meter 2	Speed	Braking Force	Torque on Shaft	Power on Shaft	Hydraulic Power	Efficiency
(N)	(N)	(rev/min)	(N)	(Nm)	(W)	(W)	(%)
1	0.5	1185	0.5	0.013	1.551	23.527	6.593
2	0.75	1140	1.25	0.031	3.731	23.527	15.857
3	1	1100	2	0.050	5.760	23.527	24.481
4	1.25	1020	2.75	0.069	7.343	23.527	31.213
5	1.5	975	3.5	0.088	8.934	23.527	37.974
6	2	935	4	0.100	9.791	23.527	41.618
7	2.25	885	4.75	0.119	11.005	23.527	46.778
8	2.75	830	5.25	0.131	11.408	23.527	48.489
9	3	775	6	0.150	12.174	23.527	51.744
10	3.5	725	6.5	0.163	12.337	23.527	52.440
11	4	685	7	0.175	12.553	23.527	53.358
12	4.5	640	7.5	0.188	12.566	23.527	53.413
13	5	600	8	0.200	12.566	23.527	53.413
14	5.25	530	8.75	0.219	12.141	23.527	51.605
15	5.5	465	9.5	0.238	11.565	23.527	49.157
16	6	400	10	0.250	10.472	23.527	44.511
17	6.25	310	10.75	0.269	8.724	23.527	37.083
18	6.5	235	11.5	0.288	7.075	23.527	30.073
19	7	150	12	0.300	4.712	23.527	20.030
20	7.75	0	12.25	0.306	0.000	23.527	0.000

Annex 5: Task Two Results Graph of Pelton Wheel Experiment (UWTSD) Displaying the Relationship Between Speed and Shaft Power at a Constant Head



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