Simon Fraser University

Sustainable Energy Engineering

Run-of-River Hydroelectric System Analysis

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Table of Contents

Introduction

BC has the largest number of off-grid communities in Canada. Nearly all of these communities rely heavily on diesel generators to sate their power demands, which is both economically and environmentally tolling. These communities face consistent issues with efficient and sustainable energy solutions; especially for electricity. Small-scale run-of-river systems could provide the generation requirement while reducing the emission of harmful toxins, such as NO_x and other greenhouse gases. For this report, we shall consider a remote off-grid facility requiring 100 kW of stable power supply from a hydroelectric system.

Project Description

Run-of-river hydropower is an attractive and consistent source of renewable power. Diverting a steady, reliable, and minimal amount of water from alpine streams, run-of-river (RoR) can help play a role in the green energy transition.

In order to design a RoR system, we must first ensure that we define the requirements.

- Net electrical power delivered: $\dot{W}_{produced} \geq 100\ kW$
- Stream diversion maximum: $Q_{diverted} \leq 0.1 \cdot Q_{stream}$
- In-pipe pressure: $P_{in\text{-}pipe} < 0.9 \cdot P_{rated}$
- Minimize installed cost

We must ensure that the system we design consistently meets the current facility's power demands of 100 kW. However, we must also ensure that we do not divert more than 10% of the flow in any stream in our location; doing so could have a large impact on the local environment. Additionally, we must also make certain that our system is safe: we will limit in-pipe pressures for our RoR system to 90% of their max rated value. Finally, we shall minimize the installed cost for this system, thus maximizing its return on investment.

Our RoR system is governed by the following equation, titled the ***Energy Equation***:

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + h_{turbine} + h_L + h_m$$

Both the inlet and exit pipes for our system shall be open to the atmosphere ($P_1 = P_2 = P_{atm}$), allowing for these terms to cancel. Due to the law of conservation of mass, negligible change in pipe diameter and fluid density means that the difference in velocities is negligible, thus those terms can be removed as well. Rearranging for head available to the turbine, the equation simplifies to the following:

$$H_{net} = h_{turbine} = (z_1 - z_2) - h_{friction\ loss} - h_{minor\ loss}$$

Expanding both the Darcy-Weisbach frictional losses (h_L) and minor loss terms, our energy balance becomes the following:

$$H_{net} = \Delta z \; - f(\frac{L}{D})(\frac{V^2}{2g}) - \sum K_L(\frac{V^2}{2g})$$

Each term in the right-hand side of this equation represents a design lever that can be manipulated to find potential configurations for our RoR system. Geometry of the landscape dictates both Δz and L, while choices in both material and size will influence h_L and h_m, through roughness-to-diameter ratio, diameter influencing the velocity, and coefficients of loss for valves. For calculations of friction factor (f), the Haaland equation was used as a high-level approximation (see Appendix E).

Once solved, we can then apply the net energy for the turbine to find the power generated. Turbine efficiency is found through the turbine efficiency curves given in the project description, and is dependent on flow rate, head, and turbine type.

$$\dot{W} = \eta \rho g Q H$$

We shall design our system for the worst-month case as the relevant design point to consider, as all other months with higher flow rates could be implicitly hit; simply by including valves in our design to regulate flow rate such that we reliably produce 100 kW.

Design Process

To guide the decision making process, we started by analyzing the energy equation and the trade-offs that are needed to find the best configuration given the constraints.

Longer pipe lengths will incur greater frictional losses, especially in cases of smaller diameter given the relationship of pipe length-to-diameter (L / D) in the Darcy-Weisbach equation (see Appendix E). Longer pipes also have higher costs associated due to their higher pressures; gravity increases pressure with increased depth. Diameter influences fluid speed through conservation of mass, with higher velocities resulting in lower pressure given the Bernoulli relation. In addition, since velocity is the leading term in both major and minor loss formulas, we'd like to keep it minimal. In all cases, our concepts utilised diameters between 10 and 25 centimeters since it strikes a balance between head loss, cost, and ultimately, pressure capacity. The balance of these factors must be tuned to match the efficiency curves of each turbine, as their use-cases vastly differ. For example, the Pelton turbine is the best choice for systems with high-head, however it also has the largest upfront cost. Conversely, the Kaplan turbine offers low-cost options with maximal efficiency at low system heads. The Francis turbine provides a balanced "middle-ground" of both cost and available head.

Since the problem statement simply requires 100 kW of stable power generation, our team decided that there would be no greater utility provided by increasing the power generated by our system. Each concept presented builds upon the previous designs, with updates made through qualitative iteration based on high-level calculations.

Conceptual Designs

The first design attempts to maximise the flow rate through a cascade of turbines that matches the natural geometry of the landscape. The second considers the other end of the spectrum; investigating if the maximal possible system head coupled with the largest turbine size provides a better "economy-of-scale" for cost per kW. The third concept evaluates a stress test to discover if there exists a competitive solution to the edge case of designing primarily for the drought year. Finally, the fourth design is a synthesis of the quantitative results and lessons from all former concepts.

Design Concept 1: 234F5K Quad Turbine

For this design, we considered installing four turbines at stream stages II through V, drawing from the ponds immediately above. Three medium Francis turbines were selected where the gross height between ponds is above 100 m, and one small Kaplan turbine where the gross head is less than 100 m.

Engineering Rationale

Flow rate was previously identified as a limiting constraint; this design aims to utilize the maximum amount of flow rate possible through the use of several moderately sized turbines. Given the natural geometry, Francis turbines were best suited for the higher stages, offering operational efficiencies between 65% and 75%. The added benefit of lower per-unit pipe pressures allowed for use of discount valves, and both mixed steel and PVC pipes. An engineering consideration is that power distribution across many turbines staggers maintenance demands, providing continuous power output to the community. This concept argues that the greater utilisation of flow rate will offer more power, while saving costs from being able to use lower pressure rated components.

Results

This design delivered a worst-month output of 112 kW of power across the four turbines. The installation cost of this design was $221,370, which provides a useful baseline point of reference for other concepts.

Design Concept 2: 3P5K Double Turbine

This design consists of two turbines: a large Pelton driving a substantial portion of the power generation, while a small Kaplan generates the remaining amount. The large Pelton diverts water from stream stage III, and the Kaplan at stage V, with both outlets installed at the river. The Pelton requires steel piping and standard valves, while the Kaplan can be designed with PVC pipes and discount valves.

Engineering Rationale

The Pelton turbine operates at its highest efficiency under high head conditions, which is a design that we can accommodate given the configurations possible between stream diversion and turbine location. The 490 m of gross head diverted from stream stage III would allow the large Pelton turbine to operate at nearly ~87% efficiency - a near maximum amongst all turbine combinations. The total length of pipe installed is similar to that of Concept 1, and is accompanied by reduced system costs due to requiring 2 turbines fewer. While this design aims to maximise a single large power producer, a small Kaplan turbine is still required to keep power generation above 100 kW in the low-flow winter months.

Results

This system delivers approximately 116 kW of power at a price point of $189,600, a ~14% reduction in cost when compared to the previous concept. This design validates that a higher head drop could prove more important than total flow-rate utilisation for power generation in certain cases. While a substantial improvement, this design contains inefficiencies since it exceeds the required power generation by ~15%. This indicates that a combination could exist that considers the same principles in use here, but with a smaller and cheaper Pelton turbine.

Design Concept 3: 421P Triple Turbine

Designed with the worst month of the drought year in mind, this concept is composed of one large and two medium Pelton turbines. The turbines divert at stream stages IV, II, and I respectively. Stages I and II simply divert the stream into the following pond, while stream IV is diverted straight to the river. Each section utilises steel piping and low-loss valves to minimize losses. The intake heights have also been selected to maximise the efficiency on a per kW basis.

Engineering Rationale

Three turbines were selected as the sweet spot between maximizing power generation without causing project costs to overrun to several times higher than the leading typical year designs. By utilising several Pelton turbines, both flow rate and head are maximally utilised. Though incurring a higher capital-cost, this concept serves as a benchmark for how close an integrated power generator design could get to pure hydropower production under suboptimal conditions, and allows for insight into whether the increase in cost could make the upgrades an economically favourable investment.

Results

The total cost of the system was $460,250 and delivered 74 kW of worst-month power in the drought year. This fails to hit the 100 kW target, still requiring diesel power generation. This concept best demonstrates the increase of costs associated with higher climate resilience. This is a useful negative result, as we can be assured that designing for the typical year and a moderate amount of diesel usage in drought years is the rational decision.

Design Concept 4: 2P5K Double Turbine

This configuration utilizes two turbines: a medium Pelton turbine drawing from stream stage II then discharging to pond 4, and a supplemental Kaplan turbine which diverts water from stream stage V. The Pelton turbine would utilize thin-wall steel pipes and standard valves, while the Kaplan would operate with PVC pipes and discount valves.

Engineering Rationale

This design shifts the Pelton turbine and diversion point up by one section, providing more head than the earlier Pelton configuration in exchange for a modest reduction in flow rate. This shift allows for a smaller and thus cheaper Pelton turbine to be run at extremely high efficiency. This combination should produce sufficient, albeit slightly less power. The goal here is to adjust both the turbine size and location slightly to minimize the cost as much as possible, while still achieving the 100 kW requirement.

Results

This system generates 100.6 kW of power under worst-month circumstances. In whole, this aligns with all major design requirements, and for a significantly reduced final cost of $179,800, confirming that the adjustments made not only preserved the previous best design's cost efficiency, but surpassed it (see Appendix A). This concept balances the takeaways from all previous designs culminating into a constrained optimum, providing the lowest $/kW of all evaluated options (see Appendix D, Figure 2).

Final Design

The design with the lowest installed cost that exactly satisfied all requirements - the 2P5K Double Turbine - was selected as the chosen design (see Appendix D, Figure 3 & Figure 4). This concept was further specified in order to meet all design constraints set out by the problem statement.

Components

Turbines

The system utilizes two distinct turbines to maximize energy extraction across different hydraulic regimens. The primary power producer is a medium Pelton (P2) turbine located at Pond-4. This choice was driven by the high net head ($H_{net} \approx 590$m), where the Pelton's impulse design achieves a peak efficiency of 89%. A small Kaplan (K1) turbine is situated at the Stage V river outlet. Unlike the Pelton, the Kaplan is a reaction turbine optimized for the low-head (70 m), high flow conditions of the lower stream. It operates at 78% efficiency and provides just the final "top-up" power required to hit the 100 kW threshold. During higher flow months (May-June), the control valves will throttle the intake to maintain the 100 kW setpoint, preventing over-speeding of the runners and ensuring grid stability.

Piping

Material Selection

The selection of penstock materials was primarily dictated by the hydrostatic pressure requirements of the two distinct stages of the system. For the primary Pelton stage, the static pressure at the turbine inlet reaches approximately 5.88 MPa (see Appendix E). Following the 90% pressure rating rule, PVC was rejected for this section as the operating pressures significantly exceed its safe threshold. Instead, 0.15 m ID thin-wall steel was selected; its superior tensile strength provides a substantial margin to absorb transient dynamic pressures such as water hammer. Even a high-level calculation of pressure surge suggests that with the chosen steel gauge, the system remains well within safe limits during sudden valve closures. Schedule 40 steel was briefly considered, but rejected in favor of the thinner variant since the increase in cost would be unjustified.

The same logic was applied to the Kaplan stage, though with a different outcome. Since the vertical drop in Stage V is only 70m, the static pressure is roughly 0.69 MPa (see Appendix E). In this lower-pressure regime, 0.25m ID PVC easily satisfies the 90% rule, allowing the design to meet all safety standards while significantly reducing the total capital cost compared to an all-steel configuration.

Velocity & Diameter Relation

The selection of a 0.15 m diameter for the primary penstock resulted from an optimization study balancing frictional head loss against material costs (see Appendix D, figures 5-7). While a 0.1 m diameter would lower initial expenses, it would significantly increase the relative roughness (ε). Because the physical imperfections of the pipe wall occupy a larger proportion of a smaller diameter (D), the friction factor increases, compounding the power loss to approximately 7 kW.

In fluid mechanics, both minor and major head losses are proportional to the square of velocity (h_L , $h_m \propto V^2$); therefore, doubling the diameter reduces the velocity fourfold and dramatically cuts friction. Conversely, increasing the diameter to 0.2 m or 0.5 m further reduces relative roughness and velocity, but these marginal gains do not justify the increase in pipe cost. The 0.15 m threshold represents the point of diminishing returns where the cost of larger steel is no longer offset by the value of incremental power. This same logic was applied to the Kaplan stage, where a 0.25 m diameter was selected to maintain low velocities and a low relative roughness profile in the PVC section, ensuring minor losses remain small.

Friction Factor

While the friction factor is a small coefficient, it still plays a major role in the pressure loss. We calculated friction factor using the Haaland equation, an accurate estimation (see Appendix E). Although the Colebrook equation is more accurate, and in fact defines the Moody diagram, it is an iterative solution. The Haaland equation is therefore used throughout this report for simplicity in Excel, where many designs were tested.

Minor Losses

While minor losses do not affect the system as much as the major losses, they result in a greater contribution due to the addition of control valves. The minor losses were determined by the K_L coefficients and calculated using $h_L = K_L(V^2/2g)$ (see Appendix E). These losses came from the movement of fluid through the valves, as the valves had a specific minor loss coefficient depending on the type. Although our group did not account for any bends or elbows in the system, these minor losses are negligible compared to the losses by the flowing fluid through the valves.

Controls

The control system integrates automation and safety to ensure stable power delivery and regulatory compliance. Automated 0.15m (Stage II) and 0.25m (Stage V) control valves are installed in-line, downstream of the initial gate valves, to modulate flow into the Pelton and Kaplan turbines. These valves are linked via a feedback loop to flow transmitters (FT), which monitor the system to maintain the 100 kW target while ensuring the 10% stream diversion limit is never exceeded (See Appendix A4).

To satisfy the safety requirement of $P_{pipe} < 0.9\ P_{rated}$ pressure transmitters (PT-101) continuously monitor the penstock. In the event of a sudden pressure spike, such as a load rejection, a pressure relief valve (PRV) automatically activates to protect the infrastructure. In the high-head Pelton stage, entrance losses from Pond-1 into Pond-4 were found to be negligible, representing less than 1% of the total head available

P&ID

The P&ID, located in Appendix A3, illustrates the “2P5K Double Turbine” architecture designed to maximize head while ensuring automated safety and compliance. The Pelton turbine system begins at Stage II, where a gate valve and flow transmitter (FT) work in tandem with the primary 0.15 m standard control valve to maintain the 10% stream diversion cap. The control valve was placed before the turbine to stabilize the flow. As the water descended the 1,450 m penstock, a pressure transmitter (PT) was placed in “parallel” to monitor the 5.88 MPa of static head to protect pipe integrity.

To prevent overpressurization during transient events, such as a turbine trip, a pressure relief valve (PRV) is positioned to divert the flow to a dedicated drain box. The transition between stages is managed by a back pressure regulator, which ensures a steady discharge pressure from the Pelton turbine before the water enters Pond-4. This setup allows the supplemental Kaplan turbine to receive a stable flow, providing the final power "top-up" required for the 100 kW target while shielding the downstream PVC components from high-pressure surges. The Kaplan turbine has a similar pressure protection system as the Pelton (see Appendix A3).

Bill of Materials

The Bill of Materials, summarizes a total capital investment of $179,800 for the hydro-mechanical installation (see Appendix A1). This includes a list of each component used in the system, its unit cost, and quantity. Instrumentation such as pressure and flow regulators are also included, with the assumption that any associated costs are implicit within the cost of valve selection. We achieved a cost-effective design through the strategic use of materials and equipment. Key examples include:

- Utilising 0.25 m PVC piping for the final 800 m run where pressures are low enough to avoid the high costs of steel.
- Using discount valves on the Kaplan turbine as the minor loss penalty was insignificant, and pressures remained in range.
- Opting for a medium Pelton turbine, forgoing unnecessary power generation for a reduction in capital cost.

Financial Assessment

A detailed financial assessment has been conducted for this design, with a few necessary assumptions.

First, we shall consider a lifetime of 20 years for our hydropower system. This is a fair assumption, since large-scale maintenance is typically required on timelines of around this time scale. Since the project description explicitly labelled maintenance is out of scope, we elected to consider a timeline of 20 years for both simplicity and accuracy (see Appendix C).

Secondly, we've assumed no operating costs. Operating costs for hydropower systems could range from maintenance, operator labour, to replacing parts. This is simply assumed to be negligible, as stated in the project description. Therefore, with no maintenance considerations, we can also assume a 100% capacity factor.

After running our economic analysis, we found some key values. The levelized cost of electricity, or LCOE, was calculated to be 1.65 ¢/kWh. While this is quite low, it is still within the realm of reason; current BC electricity price is around 10-15 ¢/kWh. Using this LCOE, and the price of electrical energy for the diesel generator being 1 $/kWh, we found a net savings of 98.35 ¢/kWh. Extending this value to the RoR system's lifetime of 20 years, we found a ROI value of 94.84 (see Appendix A3).

Greenhouse Gas Assessment

To ensure that our design outperforms the purely diesel reliant system, we must perform a detailed Greenhouse Gas (GHG) assessment. This is included in our appendix (see Appendix A2).

Firstly, we calculated the amount of power that our system is lacking in the drought year. This was found to be 3.75 MWh. Next, finding the CO_{2e} emissions, we simply multiplied this power by the emissions intensity of the diesel generator. This yielded us an answer of 66.3 tons of CO_{2e} per drought year. This is considerably smaller than the 644.7 tons of CO_{2e} for running only the diesel generator year-round. In effect, we've avoided emitting 579 tons of CO_{2e} with our RoR system in the drought year, while the normal year abates 645 tons of CO_{2e}.

Drought year

The impact of a "drought year", characterized by a 40% reduction in water flow rate, was a primary factor in the system's sizing. Under these conditions, hydroelectric output is projected to fall below threshold in four months. In the worst month – December – the system only generates 58 kW, leaving a 42 kW deficit that must be met by the Generac SD100 backup generator. While this hybrid mode consumes approximately 96,852 liters of diesel annually and emits 263.44 tonnes of CO2, it remains the most rational economic choice. Attempting to over-build the hydro capacity to meet a 100 kW load during a 1-in-10-year drought would require significantly larger turbines and penstocks; the costs of which would far exceed the occasional expense of supplemental diesel.

Hazards and Risks

While our system has been designed with safety and efficiency in mind, there are still certain aspects of the design whose risks must be considered.

Natural Risks

As our system resides outdoors year-round, some key risks require analysis related to natural disasters. Our P&ID safety controls design must accommodate force majeure events such as flooding, storms, and wildfires. These risks have been accounted for, and are explored in more detail in Appendix F.

System

Due to the pressure limitations in each of the components, we must assure ourselves that our system won't be overpressurized. As mentioned previously, if such an event like a turbine trip were to occur, the pressure coming in could exceed the rated static pressure of the pipe. This could lead to damaging or possibly breaking the pipe walls, causing a shatter failure. Additionally, if the overpressurized fluid were to enter the turbine, it could lead to mechanical fatigue of the $60,000 mechanism. If the back pressure regulator (BPR) were omitted, the high-pressure surges from the steel penstock would likely translate directly into the lower-pressure stage, causing the 0.25 m PVC piping to shatter as it exceeds its 0.8 MPa rating. Additionally, the BPR prevents cavitation at the Pelton discharge and ensures a stabilized flow into the Kaplan stage, without which the two turbines would desynchronize and fail to maintain the constant 100.6 kW output.

Turbine

As the turbine is in use year-round, ensuring it is in proper working condition is paramount to the operation of this power station. Hazards with the turbine could include overheating, debris build-up, and corrosion.

Valves

Due to the transient regulation of system flow rates, cyclic fatigue can accumulate in components, which may result in failure under a significantly lower stress than is accounted for in any single instance. Failure to regulate flow rates could result in damage to the turbine, and necessitate a costly replacement. Routine maintenance, or even use of a strain gauge could be considered as mitigation tools, however this is excluded from the scope of this project (see Appendix C).

Conclusion

The proposed two-stage hydroelectric system successfully meets the off-grid facility's 100 kW power requirement through a strategically optimized double turbine architecture. By utilizing both a high-head Pelton turbine and a low-head Kaplan turbine, the design maximizes the site's natural topography while adhering to the strict 10% stream diversion limit.

The engineering rationale focused on balancing hydraulic performance with capital efficiency. The selection of 0.15 m thin-wall steel and 0.25 m PVC penstocks, regulated by a BPR and PRV, ensures a safe operating environment that protects the $179,800 mechanical investment from overpressurization and fatigue. Our diameter optimization study confirmed that the chosen pipe sizes reside at the optima of the cost-vs-performance curve, reclaiming a significant head without incurring the increased costs of oversized piping.

Overall, our system abides by the constraints set out by the project description and seeks to maximize cost effectiveness. The turbines, piping, and controls we selected were hand-picked to ensure maximal safety, effectiveness, and efficiency.

Appendix

The appendix includes all data references from our report. It includes referenced data, third-party sources, and tables.

Appendix A: Data and Tables

A1. Tables

Table A1.1 Monthly Flow Rate for Each Stream Stage

Month	I	II	III	IV	V
January	0.08	0.15	0.23	0.29	0.50
February	0.08	0.16	0.24	0.33	0.55
March	0.14	0.27	0.45	0.54	0.90
April	0.44	0.77	1.10	1.32	2.20
May	0.96	1.22	1.72	1.98	3.30
June	1.26	1.44	1.84	2.16	3.60
July	0.48	0.72	1.32	1.44	2.40
August	0.27	0.54	0.90	1.08	1.80
September	0.18	0.36	0.60	0.72	1.20
October	0.14	0.27	0.45	0.54	0.90
November	0.11	0.23	0.38	0.45	0.75
December	0.09	0.14	0.21	0.34	0.55

Note: all entries are in m^3/s and represent the values for an average year.

Table A1.2 Stream Stage Elevation

Stream Stage	Top elevation (m)	Bottom Elevation (m)	Distance Between (m)
I	2090	1860	1300
II	1860	1680	300
III	1680	1470	450
IV	1470	1260	700
V	1260	1190	800

Table A1.3 Diesel Generator Specifications

Parameter	Value
Make / Model	Generac SD100
Displacement	6.7 L
Power	100 kW
Rated Speed	1800 RPM
BMEP	11.4 bar
Fuel	Diesel
Fuel Consumption	230 g_{diesel}/kWh_{elec}
Greenhouse Gases	3.2 g_{CO2e}/g_{diesel}

Table A1.4: Bill of Materials (BOM) for Chosen System (2P5K Double Turbine)

Category	Element ID	Part Name	Quantity	Unit Cost	Cost
Controls	CV-101	0.15 m Standard Control Valve	1 Unit	$1,800	$1,800
Controls	CV-102	0.25 m Discount Control Valve	1 Unit	$900	$900
Controls	FT-101	Flow Transmitter	1 Unit	-	Included in Controls
Controls	PT-101	Pressure Transmitter	2 Units	-	Included in Controls
Piping	L-101	0.15 m ID Thin Wall Steel Pipe	1,450 m	$50 / m	$72,500
Piping	L-102	0.25 m ID PVC Pipe	800 m	$37 / m	$29,600
Turbine	T-01	Medium Pelton Turbine (P2)	1 Unit	$60,000	$60,000
Turbine	T-02	Small Kaplan Turbine (K1)	1 Unit	$15,000	$15,000
Isolation	GV-101	Gate Valve	2 Units	-	Included in Isolation
Safety	PRV-101	Pressure Relief Valve	1 Unit	-	Included in Safety
Safety	BPR-101	Back Pressure Regulator	1 Unit	-	Included in Safety
Total Project Cost:	-	-	-	-	**$179,800**

A2. Greenhouse Gas Emissions

The following calculation is the tons of CO_{2e} emitted by purely using diesel power generation:

Hours in a year:
8760 h

kWhs used per year:
8760 h x 100 kW = 876,000 kWh

Grams of diesel used:
876,000 kWh x 230gCO_{2e} / kWh = 201,480,000 gCO_{2e}

Tons of CO_{2e} emitted:
201,480,000 x 3.2 / 1,000,000 = 644.736

⇒ The current system emits 644.736 tons of CO_{2e}

This calculation is for the emissions of our system in the drought year:

Missing generation:
90,096 kWh

Grams of diesel used:
90,096 kWh x 230 gCO_{2e} / kWh = 20,772,080 g_{diesel}

Tons of CO_{2e} emitted:
20,772,080 g_{diesel} x 3.2 gCO_{2e}/g_{diesel} / 1,000 g/kg

= 66,310.66 kg CO_{2e}

⇒ In the drought year, 66.3 tons of CO_{2e} are emitted

A3. Financial assessment

LCOE

$$\text{LCOE} = \frac{C_0 \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1}}{E_{Annual}}$$

C_0 = Upfront cost:
= \$179,800

n = Lifecycle:
= 20 years

i = Interest rate:
= 5% (typical value)

E_{annual} = Annual electricity production:
100 kW · 24h / day · 365 days / year
= 876,000 kWh / year

Now combining:

$$\text{LCOE} = \frac{179\,800 \cdot \frac{0.05 \cdot (1+0.05)^{20}}{(1+0.05)^{20} - 1}}{876\,000}$$

= 0.01646988262 \$ / kWh

⇒ The levelized cost of electricity for our hydropower system is: 1.65 ¢ / kWh

Savings

Cost of diesel generator - LCOE

= 1\$ / kWh - 0.016 \$ / kWh

= 0.9835301174 \$ / kWh

Total Savings = 98.35 ¢ / kWh

ROI

$$\text{ROI} = \frac{Total\ Revenue - Total\ Cost}{Upfront\ Cost}$$

However, since this accounts for continual costs, such as maintenance, we can simplify to the following:

$$\text{ROI} = \frac{Total\ Revenue - Upfront\ Cost}{Upfront\ Cost} = \frac{Total\ Revenue}{Upfront\ Cost} - 1$$

We can calculate total revenue as the following:

Total Revenue:
=(Cost of electricity - Production Cost) · Production Quantity

= (Savings) · Annual electricity production · Lifetime

= 0.9835301174 $ / kWh · 876 000 kWh / year · 20 years

= 17 231 447.66 $

Thus, ROI is:

$$\text{ROI} = \frac{17\ 231\ 447.66}{179\ 800} - 1$$

ROI = 95.8367 - 1

ROI = 94.84

Key assumptions:

- The project definition explicitly states that: “Ongoing maintenance or upkeep of the equipment or systems” is out of scope. Thus, we have assumed no operating costs.
- We’re assuming a lifetime of 20 years. Past 20 years, maintenance will be necessary, but it is specifically labelled as out of scope. Thus, to retain realism, we’ve elected to keep our system to a 20 year lifetime.
- Inflationary effects have been ignored for revenue.

A4. P&ID

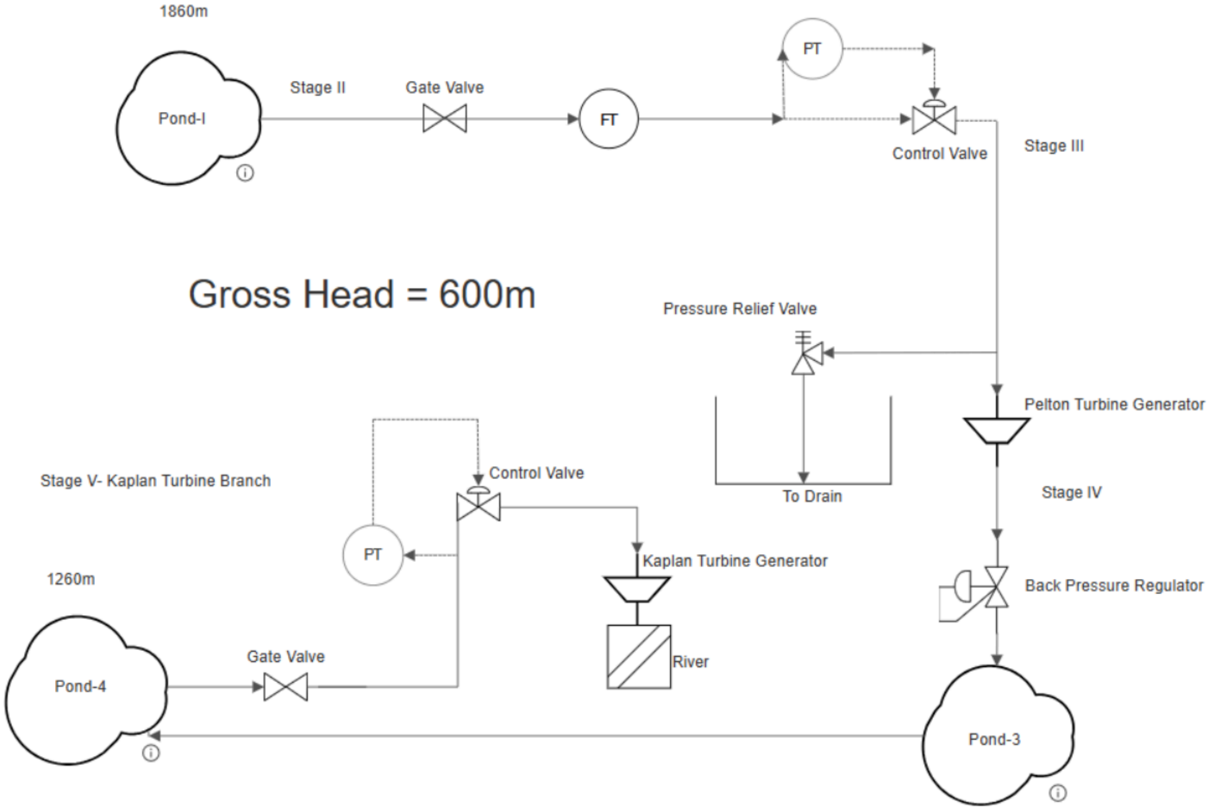


Figure 1: 2P5K Double Turbine Process & Implementation Diagram

Appendix B: Bibliography

Government of Canada. (2011). *Status of remote/off-grid communities in Canada*. Natural Resources Canada. https://natural-resources.canada.ca/sites/nrcan/files/canmetenergy/files/pubs/2013-118_en.pdf

Figure 3 is taken directly from the project description document. We have overlaid some simple lines on top to showcase the potential path for the pipes, as well as the controls, turbines, and other components. We do not claim to own the original, unedited image.

B1. AI Disclosure

Google Gemini AI was prompted to generate the rendering: *"Figure 4: 2P5K Double Turbine Hydroelectric Design Concept Rendering".*

Prompts Used:
Message 1: *"Make a rendering of the hydropower system mapped in this diagram, with the Pelton at the P, and a Kaplan at the river. Render the landscape with the turbine, pipes and power lines. This is a run-of-river off-grid hydroelectric system capable of generating 100kW of power."*

Message 2: *"Get rid of 3/4 of those boxes. Most are irrelevant or have typos, and the minimal flow of river in bottom right."*

Message 3: *"No I wanted you to do that for the RENDERING you made as the rendering was good but messy with text boxes, also higher definition rendering. Cartoon Realism"*

Appendix C: Project Exclusions

The project scope excludes the following:

- Design or cost for the preparation of any water retention (dam) or flow separation / protection in the lake, ponds, or river;
- Ongoing maintenance or upkeep of the equipment or systems;
- Building of access roads or equivalent;
- Procurement, installation or efficiency of power conversion or electrical distribution systems;
- Environmental assessment, permitting and governmental engagement;
- Engagement and consultation with Indigenous organizations and local First Nations;
- System removal and site remediation at end of life.

Appendix D: Figures & Visuals

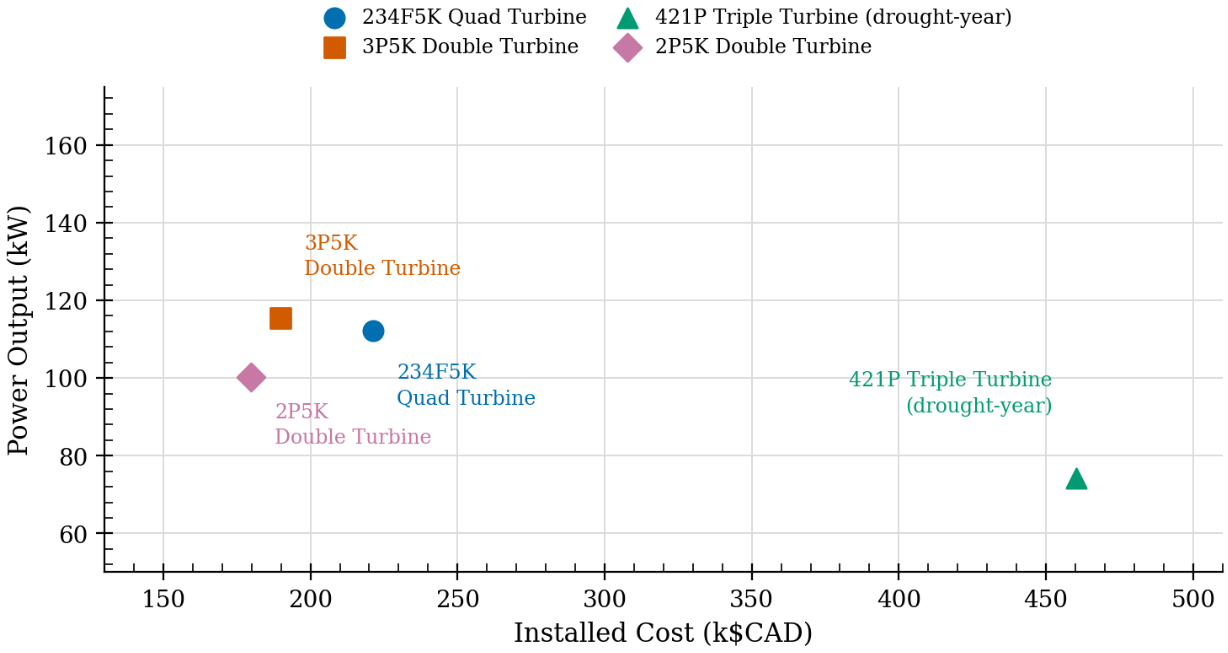


Figure 2: Power Output (kW) v.s. Installed Cost (k$CAD) for Conceptual Designs

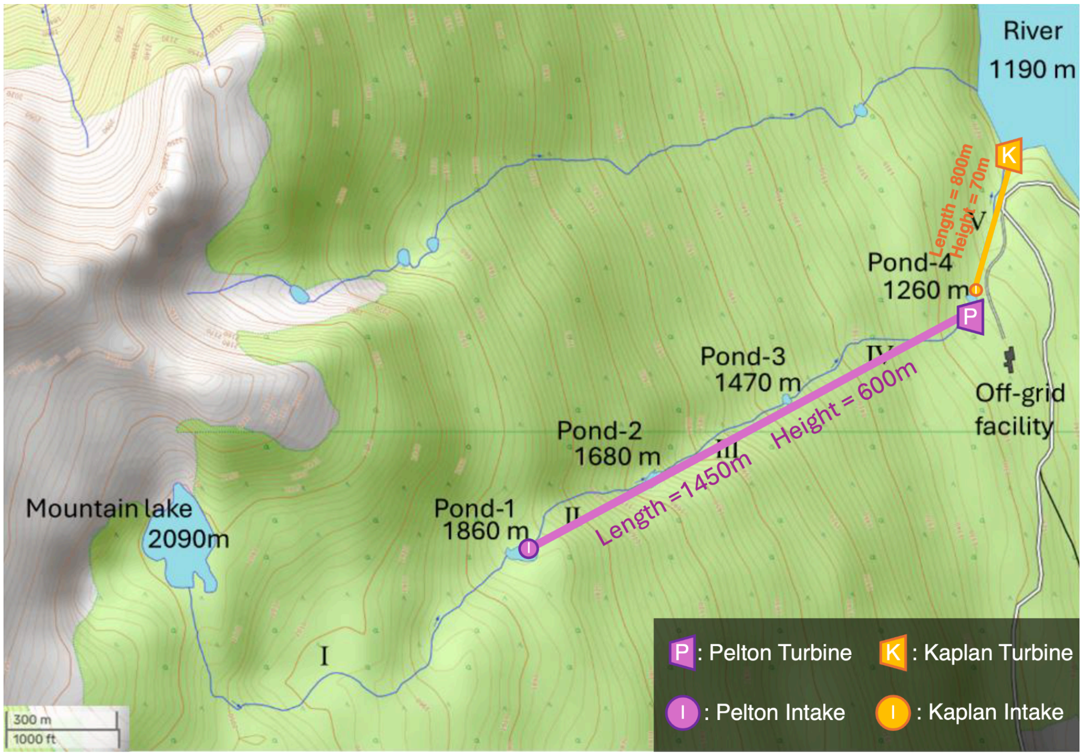
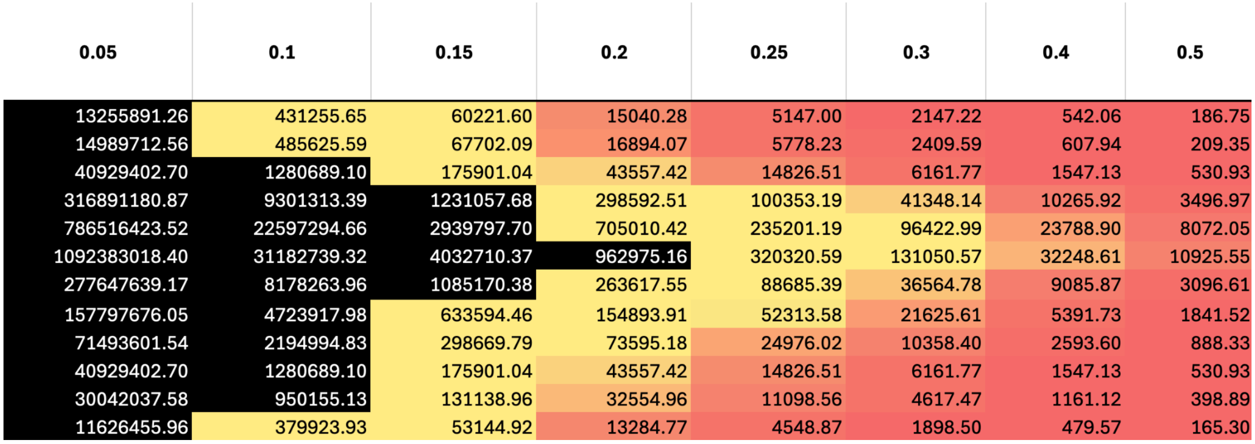


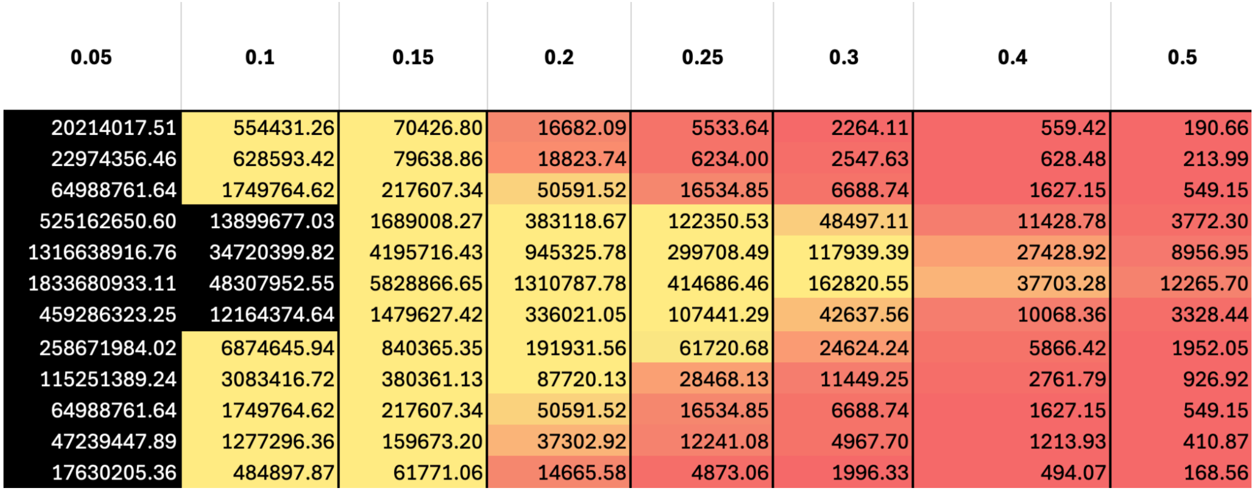
Figure 3: 2P5K Double Turbine Hydroelectric Design Concept Overlay

Figure 4: 2P5K Double Turbine Hydroelectric Design Concept Rendering



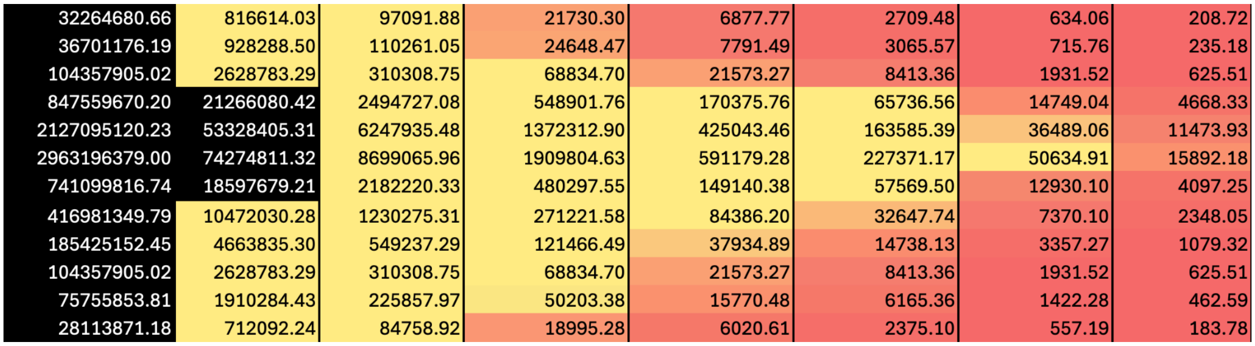
0.05	0.1	0.15	0.2	0.25	0.3	0.4	0.5
13255891.26	431255.65	60221.60	15040.28	5147.00	2147.22	542.06	186.75
14989712.56	485625.59	67702.09	16894.07	5778.23	2409.59	607.94	209.35
40929402.70	1280689.10	175901.04	43557.42	14826.51	6161.77	1547.13	530.93
316891180.87	9301313.39	1231057.68	298592.51	100353.19	41348.14	10265.92	3496.97
786516423.52	22597294.66	2939797.70	705010.42	235201.19	96422.99	23788.90	8072.05
1092383018.40	31182739.32	4032710.37	962975.16	320320.59	131050.57	32248.61	10925.55
277647639.17	8178263.96	1085170.38	263617.55	88685.39	36564.78	9085.87	3096.61
157797676.05	4723917.98	633594.46	154893.91	52313.58	21625.61	5391.73	1841.52
71493601.54	2194994.83	298669.79	73595.18	24976.02	10358.40	2593.60	888.33
40929402.70	1280689.10	175901.04	43557.42	14826.51	6161.77	1547.13	530.93
30042037.58	950155.13	131138.96	32554.96	11098.56	4617.47	1161.12	398.89
11626455.96	379923.93	53144.92	13284.77	4548.87	1898.50	479.57	165.30

Figure 5: Monthly Major Loss (Pa) Heat Map of Stream Stage II with PVC Piping*



0.05	0.1	0.15	0.2	0.25	0.3	0.4	0.5
20214017.51	554431.26	70426.80	16682.09	5533.64	2264.11	559.42	190.66
22974356.46	628593.42	79638.86	18823.74	6234.00	2547.63	628.48	213.99
64988761.64	1749764.62	217607.34	50591.52	16534.85	6688.74	1627.15	549.15
525162650.60	13899677.03	1689008.27	383118.67	122350.53	48497.11	11428.78	3772.30
1316638916.76	34720399.82	4195716.43	945325.78	299708.49	117939.39	27428.92	8956.95
1833680933.11	48307952.55	5828866.65	1310787.78	414686.46	162820.55	37703.28	12265.70
459286323.25	12164374.64	1479627.42	336021.05	107441.29	42637.56	10068.36	3328.44
258671984.02	6874645.94	840365.35	191931.56	61720.68	24624.24	5866.42	1952.05
115251389.24	3083416.72	380361.13	87720.13	28468.13	11449.25	2761.79	926.92
64988761.64	1749764.62	217607.34	50591.52	16534.85	6688.74	1627.15	549.15
47239447.89	1277296.36	159673.20	37302.92	12241.08	4967.70	1213.93	410.87
17630205.36	484897.87	61771.06	14665.58	4873.06	1996.33	494.07	168.56

Figure 6: Monthly Major Loss (Pa) Heat Map of Stream Stage II with Thin Wall Steel Piping*



32264680.66	816614.03	97091.88	21730.30	6877.77	2709.48	634.06	208.72
36701176.19	928288.50	110261.05	24648.47	7791.49	3065.57	715.76	235.18
104357905.02	2628783.29	310308.75	68834.70	21573.27	8413.36	1931.52	625.51
847559670.20	21266080.42	2494727.08	548901.76	170375.76	65736.56	14749.04	4668.33
2127095120.23	53328405.31	6247935.48	1372312.90	425043.46	163585.39	36489.06	11473.93
2963196379.00	74274811.32	8699065.96	1909804.63	591179.28	227371.17	50634.91	15892.18
741099816.74	18597679.21	2182220.33	480297.55	149140.38	57569.50	12930.10	4097.25
416981349.79	10472030.28	1230275.31	271221.58	84386.20	32647.74	7370.10	2348.05
185425152.45	4663835.30	549237.29	121466.49	37934.89	14738.13	3357.27	1079.32
104357905.02	2628783.29	310308.75	68834.70	21573.27	8413.36	1931.52	625.51
75755853.81	1910284.43	225857.97	50203.38	15770.48	6165.36	1422.28	462.59
28113871.18	712092.24	84758.92	18995.28	6020.61	2375.10	557.19	183.78

Figure 7: Monthly Major Loss (Pa) Heat Map of Stream Stage II with Sched 40 Steel Piping*

**black = overpressurized, yellow = high pressure, red = low pressure*

Appendix E: Worked Calculations

Variable Values
Density:
$\rho = 1000\ \mathrm{kg/m^3}$

Gravity:
$g = 9.81\ \mathrm{m/s^2}$

Coefficient of Dynamic Viscosity:
$\mu = 0.001\ \mathrm{Pa \cdot s}$

Height of Pond 1:
$H_{Pond\ 1} = 1860\ \mathrm{m}$

Height of Pond 4:
$H_{Pond\ 4} = 1260\ \mathrm{m}$

Height of River:
$H_{River} = 70\ \mathrm{m}$

Pascal-to-MegaPascal Conversion Factor:
$1\ \mathrm{Pa} = 1 \cdot 10^{-6}\ \mathrm{MPa}$

Stream Stage 2 Flow Rate (December):
$Q_{II,\ total} = 0.14\ \mathrm{m^3/s}$

Stream Stage 5 Flow Rate (December):
$\mathrm{Q_{IV,\ total}} = 0.55\ \mathrm{m^3/s}$

Thin Wall Steel Pipe Pressure Rating (D = 0.15m):
$P_{Thin\ Wall\ Steel} = 8.6\ \mathrm{MPa}$

PVC Pipe Pressure Rating (D = 0.25m):
$P_{PVC} = 0.8\ \mathrm{MPa}$

Diameter of Thin Wall Steel Pipe:
$D_{Thin\ Wall\ Steel} = 0.15\ \mathrm{m}$

Diameter of PVC Pipe:
$D_{PVC} = 0.25\ \mathrm{m}$

Surface Roughness of Thin Wall Steel:
$\varepsilon_{Thin\ Wall\ Steel} = 0.1\ \mathrm{mm} = 0.0001\ \mathrm{m}$

Surface Roughness of PVC:
ε_{PVC} = 0.01 mm = 0.00001 m

Critical Reynolds Number:
$Re_{Critical} \approx 2300$

Length of Thin Wall Steel Piping:
$L_{Thin\ Wall\ Steel}$ = 1 450 m

Length of PVC:
L_{PVC} = 800 m

Minor Loss Coefficient for Standard Valves:
$K_{L,\ Standard}$ = 0.5

Minor Loss Coefficient for Discount Valves:
$K_{L,\ Discount}$ = 5

Minor Loss Coefficient for Sharp Entrance:
$K_{entrance}$ = 0.5

Efficiency Coefficient for Pelton Turbine:
η_{Pelton} = 0.89

Efficiency Coefficient for Kaplan Turbine:
η_{Kaplan} = 0.78

Worst Month Flow Rates → Available Flow Rates

$Q_{II,\ total} = 0.14\ m^3/s \rightarrow Q_{II,\ available} = 0.14\ m^3/s \cdot 0.10 = 0.014\ m^3/s$
$Q_{II,\ available} = Q_{II} = 0.014\ m^3/s$

$Q_{IV,\ total} = 0.55\ m^3/s \rightarrow Q_{IV,\ available} = 0.55\ m^3/s \cdot 0.10 = 0.055\ m^3/s$
$Q_{IV,\ available} = Q_{IV} = 0.055\ m^3/s$

Gross Height
$H_{gross,\ Pelton} = H_{Pond\ 1} - H_{Pond\ 4}$ = 1 860 m - 1 260 m = 600 m
$H_{gross,\ Kaplan} = H_{Pond\ 4} - H_{River}$ = 1 260 m - 1 190 m = 70 m

In-pipe Pressure

$$P_{Pelton,\ static} = \rho g H_{gross,\ Pelton} = (1000\frac{kg}{m^3})(9.81\frac{m}{s^2})(600m)(10^{-6}) = 5.89\ MPa$$
$$P_{Pelton,\ allowed} = 0.9 * P_{Thin\ Wall\ Steel,\ D=0.15m} = 0.9 * 8.6MPa = 7.74MPa$$
$$P_{Pelton,\ static} = 5.89MPa < 7.74MPa = P_{Pelton,\ allowed}$$

$$P_{Kaplan,\,static} = \rho g H_{gross,\,Kaplan} = (1000\frac{kg}{m^3})(9.81\frac{m}{s^2})(70m)(10^{-6}) = 0.687MPa$$

$$P_{Kaplan,\,allowed} = 0.9 * P_{PVC,\,D=0.25m} = 0.9 * 0.8MPa = 0.72MPa$$

$$P_{Kaplan,\,static} = 0.687MPa < 0.72MPa = P_{Kaplan,\,allowed}$$

Area, Velocity, Reynolds Number

$$A_{Thin\,Wall\,Steel} = \frac{\pi}{4}D^2_{Thin\,Wall\,Steel} = \frac{\pi}{4}(0.15m)^2 = 0.0177m^2$$

$$V_{Thin\,Wall\,Steel} = \frac{Q_{II}}{A_{Thin\,Wall\,Steel}} = \frac{0.014\frac{m^3}{s}}{0.0177m^2} = 0.792\frac{m}{s}$$

$$A_{PVC} = \frac{\pi}{4}D^2_{PVC} = \frac{\pi}{4}(0.25m)^2 = 0.0491m^2$$

$$V_{PVC} = \frac{Q_V}{A_{PVC}} = \frac{0.055\frac{m^3}{s}}{0.0491m^2} = 1.12\frac{m}{s}$$

E1. Reynold’s Number

$$\boxed{Re = \frac{\rho VD}{\mu}}$$

$$Re_{Thin\,Wall\,Steel} = \frac{\rho V_{Thin\,Wall\,Steel} D_{Thin\,Wall\,Steel}}{\mu} = \frac{(1000\frac{kg}{m^3})(0.792\frac{m}{s})(0.15m)}{(0.001Pa\cdot s)} = 118.8 * 10^3$$

$$Re_{Thin\,Wall\,Steel} = 118.8 * 10^3 \gg 2300 \approx Re_{critical} \rightarrow Turbulent\ Flow$$

$$Re_{PVC} = \frac{\rho V_{PVC} D_{PVC}}{\mu} = \frac{(1000\frac{kg}{m^3})(1.12\frac{m}{s})(0.25m)}{(0.001Pa\cdot s)} = 280 * 10^3$$

$$Re_{PVC} = 280 * 10^3 \gg 2300 \approx Re_{critical} \rightarrow Turbulent\ Flow$$

E2. Haaland equation

$$\boxed{\begin{gathered} \frac{1}{\sqrt{f}} = -1.8\,log\left[(\frac{\varepsilon/D}{3.7})^{1.11} + \frac{6.9}{Re}\right] \\ f = \frac{1}{\left[1.8\,log\left[(\frac{\varepsilon/D}{3.7})^{1.11} + \frac{6.9}{Re}\right]\right]^2} \end{gathered}}$$

** Note: the Haaland equation is an approximation for the friction factor, f. The Haaland equation was used for both simplicity and computational efficiency.*

Friction Factor

$$f_{Thin\ Wall\ Steel} = \frac{1}{\left[1.8\ log\left[\left(\frac{\varepsilon_{Thin\ Wall\ Steel}/D_{Thin\ Wall\ Steel}}{3.7}\right)^{1.11} + \frac{6.9}{Re_{Thin\ Wall\ Steel}}\right]\right]^2}$$

$$= \frac{1}{\left[1.8\ log\left[\left(\frac{0.0001m/0.15m}{3.7}\right)^{1.11} + \frac{6.9}{118.8*10^3}\right]\right]^2} = 0.0204$$

$$f_{PVC} = \frac{1}{\left[1.8\ log\left[\left(\frac{\varepsilon_{PVC}/D_{PVC}}{3.7}\right)^{1.11} + \frac{6.9}{Re_{PVC}}\right]\right]^2}$$

$$= \frac{1}{\left[1.8\ log\left[\left(\frac{0.00001m/0.25m}{3.7}\right)^{1.11} + \frac{6.9}{280*10^3}\right]\right]^2} = 0.0149$$

E3. Darcy-Weisbach Equation

$$\boxed{h_L = f\frac{L}{D}\frac{V^2}{2g}}$$

Major Loss

$$h_{L,\ Thin\ Wall\ Steel} = f_{Thin\ Wall\ Steel}\frac{L_{Thin\ Wall\ Steel}}{D_{Thin\ Wall\ Steel}}\frac{V_{Thin\ Wall\ Steel}^{\ 2}}{2g} = (0.0204)\left(\frac{1450m}{0.15m}\right)\left(\frac{(0.792\frac{m}{s})^2}{2(9.81\frac{m}{s^2})}\right) = 6.3m$$

$$h_{L,\ PVC} = f_{PVC}\frac{L_{PVC}}{D_{PVC}}\frac{V_{PVC}^{\ 2}}{2g} = (0.149)\left(\frac{800m}{0.25m}\right)\left(\frac{(1.12\frac{m}{s})^2}{2(9.81\frac{m}{s^2})}\right) = 3.0m$$

E4. Minor Loss Equation

$$\boxed{h_m = \sum K\frac{V^2}{2g}}$$

Minor Loss

$$h_{m,\ Standard} = (K_{L,\ Standard} + K_{Entrance})\frac{V_{Thin\ Wall\ Steel}^{\ 2}}{2g} = (0.5 + 0.5)\left(\frac{(0.792\frac{m}{s})^2}{2(9.81\frac{m}{s^2})}\right) = 0.0320m$$

$$h_{m,\ PVC} = (K_{L,\ Discount} + K_{Entrance})\frac{V_{PVC}^{\ 2}}{2g} = (5 + 0.5)\left(\frac{(1.12\frac{m}{s})^2}{2(9.81\frac{m}{s^2})}\right) = 0.352m$$

E5. Energy Equation

$$\boxed{\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2 + h_{turbine} + h_L + h_m}$$

E6. Energy Equation (Re-arranged for turbines)

$$\boxed{H_{net} = h_{turbine} = (z_1 - z_2) - h_L - h_m}$$

Net Head

$$H_{Pelton} = H_{gross,\,Pelton} - h_{L,\,Thin\,Wall\,Steel} - h_{m,\,Standard} = 600m - 6.3m - 0.0320m = 593.7m$$

$$H_{Kaplan} = H_{gross,\,Kaplan} - h_{L,\,PVC} - h_{m,\,PVC} = 70m - 3.0m - 0.352m = 66.6m$$

E7. Hydrodynamic Power

$$\boxed{\dot{W} = \eta\rho g Q H}$$

Output

$$\dot{W}_{Pelton} = \eta_{Pelton}\rho g Q_{II} H_{Pelton} = (0.89)(1000\frac{kg}{m^3})(9.81\frac{m}{s^2})(0.014\frac{m^3}{s})(593.7m) = 72569.5W \approx 72.6kW$$

$$\dot{W}_{Kaplan} = \eta_{Kaplan}\rho g Q_{V} H_{Kaplan} = (0.78)(1000\frac{kg}{m^3})(9.81\frac{m}{s^2})(0.055\frac{m^3}{s})(66.6m) = 28028.5W \approx 28.0kW$$

$$\dot{W}_{Total} = \dot{W}_{Pelton} + \dot{W}_{Kaplan} = 72.6kW + 28.0kW = 100.6kW$$

$$\boxed{\dot{W}_{Total} = 100.6kW}$$

Appendix F: Acts of God

Flooding

While overgeneration might sound like a positive for a power plant given that it simply has more power available, this is actually a risk we must deal with. Flooding in the reservoirs or the piping could prove harmful to the system, due to overpressurization. To ensure that our system intakes only the water necessary, we've included safety systems such as back-pressure regulators and blow off valves. While both of these components regulate pressure, the mechanism for pressure control is vastly different. Blow off valves, or BOVs, mitigate pressure spikes while back-pressure regulators, or BPRs, ensure a consistent pressure. Both are in use in our final design for added piping protection.

Storms

Electrical storms can prove highly dangerous for any power generating station. A sudden enormous increase in voltage in electrical components can have disastrous effects on the lifetime of the station. Electrical storms can be unpredictable, and having adequate circuit protection is challenging. However, to help mitigate this hazard, we could include components such as fuses to aid in voltage regulation. While this wouldn't entirely negate the risk of electrical damage, it will be mitigated.

Wildfires

Wildfires in BC are common, so common in fact that June to August is typically referred to as "wildfire season". As such, fires must be considered when conducting a risk analysis. In order to stay safe from fires, our circuits and electrical components will be housed in specialized containers, as indicated by the P&ID. These boxes will help to isolate the electronic controls from outside, which will mitigate both fire and rain damage risks.