

NAU Siting and Design Final Report

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Fall 2025-Spring 2026



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DISCLAIMER

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EXECUTIVE SUMMARY

This project evaluates the feasibility of retrofitting a non-powered dam with a modular hydropower system through an integrated siting and design approach. Three candidate sites, (John C. Stennis Lock & Dam, Peoria Lock & Dam, and Coon Rapids Dam) were assessed using a weighted decision framework incorporating hydraulic performance, infrastructure availability, environmental constraints, regulatory complexity, and economic potential.

While several sites demonstrated strong individual advantages, the selection process emphasized overall feasibility rather than maximizing a single metric such as power output. Based on this analysis, Coon Rapids Dam was selected as the optimal site, offering a balanced combination of moderate hydraulic potential, existing infrastructure, favorable energy market conditions, and manageable environmental constraints.

Following site selection, the team chose the StreamDiver, a modular, low-head turbine system designed for scalable deployment with minimal structural modification to the existing dam. The system enables controlled flow diversion through multiple turbine units, allowing flexibility in installation while maintaining environmental flow requirements.

Engineering analysis was conducted using site-specific conditions, including a net head of approximately 5 meters and a controlled flow rate of 10 m³/s, to estimate power output and identify optimal operating conditions. A scaled prototype was fabricated and tested using a recirculating flow loop and prony brake system to measure torque and rotational speed. Experimental results validated modeled performance trends and provided insight into system behavior across operating ranges.

An economic assessment was performed using levelized cost of energy (LCOE) as the primary feasibility metric. The final design achieves an installed capacity of 2.17 MW, generating approximately 12,699 MWh annually with a LCOE of \$79.61/MWh. This configuration was selected as optimal due to its balance between energy production, structural feasibility, and economic performance under site-specific constraints.

Key challenges include regulatory constraints associated with the dam's function as a fish barrier, limitations on flow diversion, and uncertainty in capital costs. However, the modular design enables phased deployment and provides flexibility in addressing these constraints.

Overall, this project demonstrates that modular hydropower systems can provide a viable pathway for converting non-powered dams into renewable energy assets, with Coon Rapids representing a strong candidate for implementation due to its balance of technical, economic, and environmental considerations.

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1 SITE SELECTION

A structured site selection process was used to identify a feasible location for a modular hydropower system based on technical, economic, and practical constraints. Three iterations were completed, refining evaluation criteria and improving site suitability with each round. Due to the repetitive nature of this process and report length limitations, only a summarized overview is presented here. Additional details are provided in the Siting Takeaway section.

1.1 Methodology

To begin our site selection, we sourced a comprehensive database of ~2,700 NPDs from the Oak Ridge National Laboratory (ORNL) called the NPD Inventory [1]. This database includes monthly head-flow data, energy potential, and location information. Due to the size of the database, manually searching was not an option, so a MATLAB program was written to filter through the dataset and give us a list of sites that fit our described bounds. While the exact values changed during each round, we filtered based on head and flow averages, and estimated power potential.

Once a shortened list of sites was created (~10-30), the team would briefly research each dam, taking note of dams that stood out for having potential. Then the top 3 to 4 dams were chosen and, using the criteria explained in section 1.2, a decision matrix was created with more in-depth research. The site with the highest score then became our site of choice.

Now that a site was selected, more rigorous analysis and research was done, including environmental analysis, power output simulations, localized cost of energy calculation, etc. Additionally, our team would reach out to the site with the goal of obtaining engineering drawings and talking to those who work directly with the dam.

The first and second iterations of this process ended up being scrapped, usually due to information learned directly from the dam managers. During each iteration, slight modifications were made to metrics, but the overall process was the same. This methodology provided a transparent and repeatable basis for site selection while incorporating key lessons learned from early stage analysis and site-specific constraints. This iterative process ensured that both quantitative metrics and real-world constraints were incorporated into the final site decision.

1.2 Selection Criteria

The selection criteria used during site selection to create a decision matrix are explained in detail below. Note, some criteria were added and/or modified during the team's three rounds of site selection, the list below only shows the final form of the criteria.

Estimated Output: Scores were found using output estimations (P) from the ORNL NPD Inventory [1]. These estimations assume 100% efficiency and are not accurate to what is realistically achievable at each site, rather this value serves as a potential meter for how much available energy is at the site. Since the main goal of our project is to generate power, this category has the largest weight in the decision matrix. More power output means a more profitable dam.

$$\text{Estimated Output Score} = P \times 10, \text{ if } P > 10 \rightarrow \text{Score} = 100$$

Flow & Head Consistency: Scores were found using monthly head and flow data from the ORNL NPD

Inventory [1]. The coefficient of variance (CV) was calculated for both head and flow rate for each dam [10]. This value gives us an idea for how reliable the input for a turbine system would be at the site. Similar to estimated output, this category has a large weighting in the matrix. This was decided as creating a dam that only generates meaningful output for a fraction of the year is both less economical and more difficult to justify.

$$\text{Consistency Score} = 1 - CV, \text{ used for head and flow scores}$$

Infrastructure Proximity: Infrastructure proximity evaluates the availability of existing structures and grid access that would support turbine integration. Sites with nearby substations, transmission lines, or existing hydropower infrastructure were scored higher due to reduced installation complexity and cost. Scoring was based off proximity to substations/transmission lines in miles, D . If the nearest connection point was on the same property as the dam, a score of 100 was assigned.

$$\text{Infrastructure Score} = 100 - (D \times 10)$$

Ownership & Regulation: This criterion assesses the complexity of ownership and regulatory requirements associated with each site. Factors considered include ownership structure, permitting difficulty, and potential regulatory barriers. Due to the qualitative nature of this criteria, scoring was determined through research and comparison to other sites, with the final score being determined by the team's opinion following this research. Dams owned by organizations such as the US Army Corps of Engineers were favored due to the ease of contact and the availability of information regarding the site.

$$\text{Ownership Score} = \text{Team Decision}$$

Dam Structure: Dam structure evaluates the physical configuration of the dam and its compatibility with the proposed turbine system. This includes considerations such as geometry, available installation locations, and the presence of flow control mechanisms. The type of dam structure (concrete, in-fill, etc.) as listed by the National Inventory of Dams was also considered in scoring [3]. Generally, concrete dams were prioritized and dams with pre-existing hydropower structures were given full or near-full scores.

$$\text{Structure Score} = \text{Team Decision}$$

Risk: The risk criterion captures potential barriers to successful implementation that are not fully represented by other criteria. This includes environmental constraints, regulatory uncertainty, structural limitations, and data uncertainty. For scoring, the Hazard Potential Classification made by the National Inventory of Dams was used [3]. This classification has three levels (HC), which were used to determine each dam's score in this category ($low\ HC = 1$, $high\ HC = 3$).

$$\text{Risk Score} = 100/HC$$

Local Need: Local need reflects the potential value of energy generation at the site, considering factors such as regional electricity pricing, demand, and community benefit. For scoring, the percent difference in dollar per kWh from the national average for each site's respective county was used (CoE) [11]. Sites with energy costs exceeding a 50% difference from the national average were either given a 0 (lower) or 100 (if higher).

$$\text{Need Score} = 50 \times (1 \pm CoE)$$

The infrastructure, ownership, risk, and local need scores all share the same weight of 12%. The reason for this was to minimize bias from the team, given that often qualitative nature of these categories. Realistically, these categories would not have equal weight, but due to the nature of this competition and the experience level of the team, this decision was meant to give us a better feel for these categories in future work. Together, these criteria capture both technical feasibility and practical implementation

considerations, reflecting the multidisciplinary nature of hydropower development.

1.3 Site Breakdown & Comparison

Peoria Lock & Dam



Figure 1: Peoria Lock & Dam [15]

Located in Peoria, Illinois, this dam is one of the few wicket dams in the United States. It stood out for having both a consistent head around 3.05 meters, and flow data around 268 m³/s generating around 2.99 MW, at least according to the ORNL database [15]. Additionally, the site is about .8 km away from the nearest grid connection. The team also managed to obtain the as-built drawings of the dam. However, after interviewing Matthew Traver, the lockmaster of the dam, the team learned that the site has a severe flood season that would often submerge much of the structure underwater. That, combined with the difficulty of integrating a turbine system into such an unusual type of dam, made this a less than ideal site for the project, but a strong initial contender.

John C Stennis Lock & Dam



Figure 2: John C Stennis Lock & Dam [14]

John C. Stennis Lock & Dam, located on the Tombigbee-Tennessee Waterway was another strong competitor. It has a much higher head around 5.5 meters and an average flow of about 226 m³/s, with a more manageable flood season compared to some of the early contenders [14]. This site does have a dry

season during autumn, but would still provide ample output throughout the year with a mean of about 3.042 MW. In terms of co-development opportunities, the dam being located in a park with unutilized plots adjacent to it gave us plenty of space for either a solar or recreational projects alongside the turbine installation. Another addition to the site would be the intertie distance of about .9 kilometers, which was within the constraints we set for the site.

When interviewing the Navigation Manager of the waterway, Roger Wilson, he stated a big issue any renovation project at the site would run into would be the conflict between navigation and energy uses, as the reservoir and tailwater have very strict heads to maintain throughout the year. Additionally, the localized cost of energy was not ideal for a profitable site. For these reasons, the team decided to perform a third round of site selection, this time with the cost of energy as a higher priority.

Coon Rapids Dam



Figure 3: Coon Rapids Dam [13]

Coon Rapids Dam, located in Coon Rapids, Minnesota, is a former hydroelectric dam. Built in the early 1900s, the powerhouse has since been dismantled and the turbines removed. The dam and its surrounding area is now a park. Fortunately, the turbine housing is still intact, though sealed off, and the onsite substation structure is also present. From the ORNL database shows the site is low-head around 5.8 meters and high-flow with an average around 300 m³/s [10]. Furthermore the intertie distance would be just under .6 kilometers cutting the expenses to a more favorable region. Another benefit when compared to the previous two dams is that Coon Rapids is not used for navigation or flood control, meaning less compromise would need to be made between uses when installing a turbine system.

After contacting the dam, we were able to obtain the original engineering drawings of the dam from the site owners and talk to the current site manager, Tim Chambers. Chambers gave us valuable information regarding the current state of the dam and the local importance of the site and surrounding park to the city of Coon Rapids

1.4 Decision Matrix & Final Selection

Table 1: Summarized Decision Matrix

Criterion	Weight	Peoria Lock & Dam		Coon Rapids Dam		John C. Stennis Dam	
		IL01014		MN00507		MS03056	
		Score out of 100	Weighted Score	Score out of 100	Weighted Score	Score out of 100	Weighted Score
Estimated Mean Output	25%	45.58	11.40	100	25.00	100.00	25.00
Flow Rate Consistency (1-CV)	7.5%	60.68	4.55	50.80	3.81	38.26	2.87

Head Consistency (1-CV)	7.5%	76.49	5.74	87.43	6.56	38.26	2.87
Proximity to Infrastructure	12%	90.00	10.80	100.00	12.00	90.00	10.80
Ownership and Regulation	12%	65.00	7.80	70.00	8.40	80.00	9.60
Structure	12%	70.00	8.40	90.00	10.80	70.00	8.40
Risk	12%	90.00	10.80	67.00	8.04	67.00	8.04
Local Need	12%	80.00	9.60	28.00	3.36	28.00	3.36
Total	100%		69.08		77.97		70.94
Rank		3		1		2	

After reviewing each site, our team decided that Coon Rapids Dam was our strongest option and the decision matrix in Table 1 supports this decision. The summarized key strengths of the site and their impact on our design are below:

Pre-Existing Hydropower Infrastructure - The remaining powerhouse and onsite substation set allow for significant savings in the cost of retrofitting. Our design strategy was to use the retired turbine housing for our system, ideally with minimal impact on the dam’s outward appearance to preserve the surrounding park’s aesthetic.

High Flow Rate, Low Head - Coon Rapids Dam has a very high, and fairly consistent, flow rate with a low head of 3-5 meters. This guided our turbine selection towards a Kaplan turbine.

Minimal Conflict Between Uses - Currently, the main use for Coon Rapids Dam is as a fish barrier against invasive carp. To account for this, construction would require a sound stoplog system and a fish screen was incorporated into each turbine housing to prevent upstream migration while the turbines are not operating.

After taking these strengths into account, as well as our goal for a cost-effective design, we chose the Voith StreamDiver for our site design. The streamdiver benefits from low-head and high flow while staying cost efficient and with a small enough footprint to be installed in the pre-existing structure.

1.5 Risk Identification & Mitigation

Risk analysis was conducted to identify site-specific constraints that could prevent successful implementation, beyond those captured in the decision matrix. The initial focus of the analysis was Peoria Lock & Dam, which was selected based on data availability and its perceived suitability for hydropower integration. Preliminary evaluation and modeling were performed for this site; however, further investigation revealed that the presence of wicket gates introduced significant challenges for integration with the proposed turbine system. The gates were required to be actively managed by a member of USACE, meaning hydropower installation would risk interfering with navigation and flood control operations. Mitigation strategies would require significant structural and operational changes. One approach could be the retrofit or partial replacement of one of the wicket gate assemblies with fixed structures that provide more stable flow conditions. Alternatively, a dedicated intake structure located downstream of the gate system could isolate turbine operation from gate controlled flows. However both strategies bring high capital costs, regulatory complexity, and operational conflicts with USACE control requirements.

Further results led the project scope to investigate John C. Stennis Lock & Dam, due to its tightly regulated head height and navigational USACE oversight. The design would falter when relying on regulated flows leading to insufficient power generation over time, and thus causing friction when implementing hydraulic equipment on site. Mitigation strategies focus on utilizing a wide operational range of modular turbines allowing for efficient performance under variable discharge conditions.

Additionally localized intake control structures could help stabilize inflow to the turbines. However due to the site's resilience on navigational driven operation, these measures would only partially eliminate the issue. The constraint remains that hydropower is second to navigation and cannot take priority, making long term performance uncertain.

Coon Rapids Dam presents a more favorable hydraulic environment but introduces environmental and recreational risks due to its location within a public park. Key concerns include aquatic species interaction, particularly invasive carp, as well as public safety and permitting constraints. Mitigation strategies focus both on ecological protection and safe integration into a recreational setting. To address fish interaction, the design can introduce fish exclusion screens and intake velocity control, preventing aquatic species from entering the turbine system while maintaining downstream passage. Since invasive carp are restricted to downstream regions, maintaining unidirectional flow conditions and screening systems ensures they are not transported upstream through the turbines. Public safety risks can be mitigated through internal turbine placement, minimizing exposure to park users, along with protective barriers, signage, and controlled access zones near intake locations. Additionally, the use of an internally drilled intake configuration significantly reduces visual impact and avoids major structural additions, supporting smoother permitting and community acceptance.

1.6 Siting Takeaways

Site selection was a difficult, though highly informative, endeavor for our team. Due to the inherent complexity of hydropower projects, analysis based purely on numbers was often ineffective. Our first site, Peoria Lock & Dam showed us that. When looking at the water data at the dam, it looked great. High flow rate, very consistent, but once we delved into the more qualitative information, problems began to appear. We learned the unique nature of wicket dams and the extreme flood seasons the site experienced. During our future iterations, we learned to take qualitative information into account of decisions.

The next site we examined, John C. Stennis Dam, demonstrated the delicate balance NPD conversion projects must achieve. While talking with the navigation manager in charge of the site, we learned the heavy restrictions in place regarding the head difference between the upstream and downstream side of the dam and that they were in place to ensure the waterway was navigable by boats throughout the year. This taught us the importance of finding sites that are capable of adding a turbine system to their other uses.

In terms of engineering, we learned the challenge and value digital models provide. Throughout the site selection process, one of our most valuable tools was the MATLAB simulation we created that used real-world data to estimate the daily and annual energy output. Creating tools like this will be essential in our engineering careers.

Overall, we learned that analyzing a site, whether it be an existing dam or for the construction of a new dam, is a complex process that requires both reliable information regarding flow and head characteristics and thorough knowledge of the various factors that can influence, limit, or outright prohibit construction. Oftentimes balancing qualitative and quantitative properties of a site requires experience and thorough analysis to understand when a factor disrupts a system or not. We also learned the importance of communicating with local experts about a site. In all of our site selection iterations, talking to the dam owners/managers was an essential part of the process. The most valuable information we learned was from those that worked with the dam daily.

2 SYSTEM DESIGN

2.1 Design Overview

The primary design objective was to maximize energy generation while maintaining structural integrity, minimizing environmental impact, and operating within regulatory constraints. The proposed system integrates a modular hydropower solution into the structure of Coon Rapids Dam by naturally diverting a controlled portion of flow through localized openings. Approximately 15% of the total river discharge is guided into turbine modules where energy is extracted before being discharged downstream, enabling power generation while maintaining overall dam operation. This diversion level was selected to balance power generation potential with environmental and operational constraints at the site. As shown in Figure 4, a guided intake geometry is used to redirect flow smoothly into the turbine, reducing head losses associated with abrupt changes in direction. This geometry ensures smooth flow transition into the turbine while minimizing turbulence and energy loss. The Voith StreamDiver turbine system was selected for this project due to its strong compatibility with low-head, high flow river environments such as the Coon Rapids Dam site. This selection ensures operation within the site's low head regime without requiring significant civil modification. Unlike conventional hydropower turbines that require significant hydraulic head and large civil structures, the Streamdiver is specifically engineered for heads in the range of 2-10 m, aligning with the available net head of 5.8 m at the site. This directly reflects the low-head conditions identified during site selection and reinforces compatibility between site characteristics and turbine design.

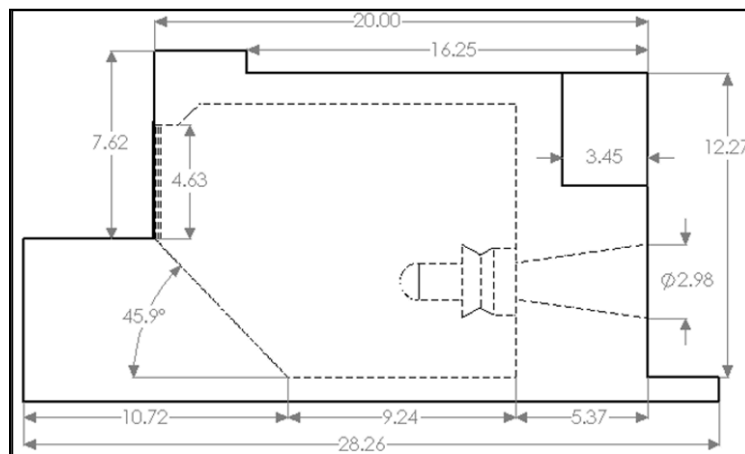


Figure 4: Turbine module cross-section showing intake geometry and flow path

Each unit functions as a self-contained module composed of an intake, turbine generator assembly, and outlet. The angled intake and confined flow passage promote gradual acceleration into the turbine region, improving flow consistency and predictability within each unit.

Rather than relying on a single installation, multiple modules are distributed along the dam structure (Figure 5). This configuration allows scalability based on flow availability and structural limitations while reducing the impact of any individual penetration. This reduces localized structural stress compared to a single large penetration and improves system resilience by distributing load and flow across multiple units. This modular approach allows the system to adapt to variable flow conditions while maintaining

consistent performance and minimizing structural impact on the dam.

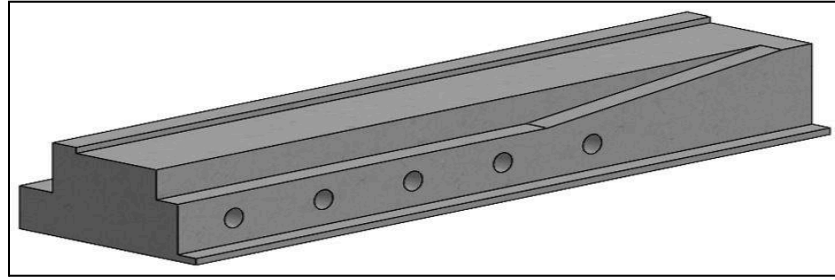


Figure 5: Turbine modular system layout showing distributed turbine openings along the dam structure

This modular configuration was selected over a single large turbine to reduce structural modification requirements, distribute hydraulic loading across multiple locations, and allow flexible operation under varying flow conditions.

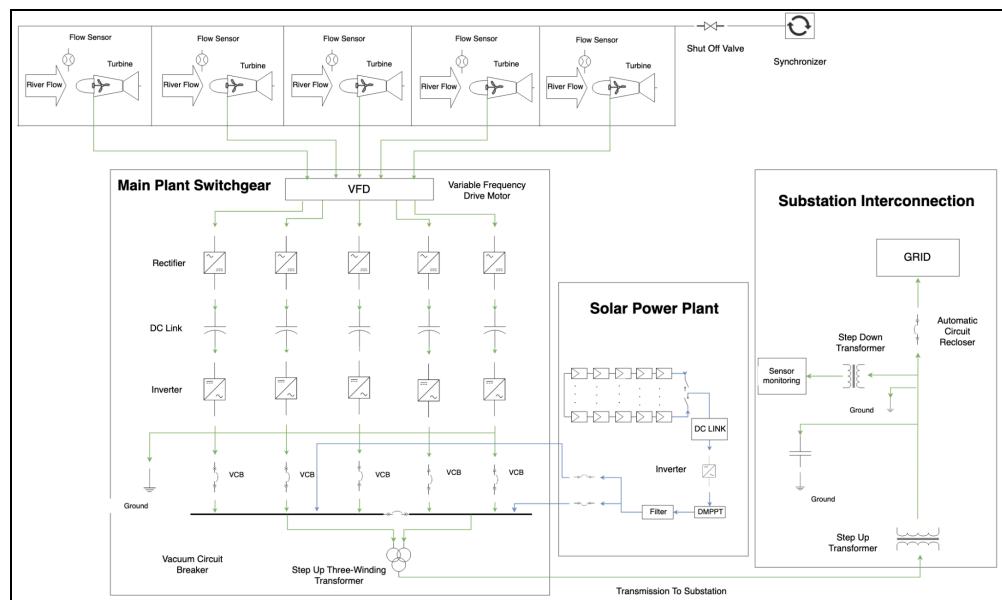


Figure 6: Power flow diagram of Coon Rapids dam

Figure 6 shows a complete overview of the electrical system operation and grid connection of the hydroelectric dam. Mechanical power is generated by the Voith StreamDiver and converted to electrical power through the permanent magnet synchronous generator (PMSG). Flow sensors communicate with the variable frequency drive to control the wicket gates and maintain the desired turbine speed. Inside the main plant switchgear, a two-stage rectifier and inverter are used to regulate the three-phase AC voltage. The main bus system includes a bus tie that allows for power production despite the availability of some turbines. The voltage is stepped up twice, to 13.8 kV and then 115 kV, where it is distributed to the local grid through the nearby substation. The solar power plant consists of a single sub array consisting of 24 modules in a string and 25 strings connected in parallel. It will have a single stage inverter to obtain AC voltage before it is connected to the main bus system inside the switchgear. This integrated configuration

ensures efficient energy conversion while maintaining operational flexibility under varying flow conditions.

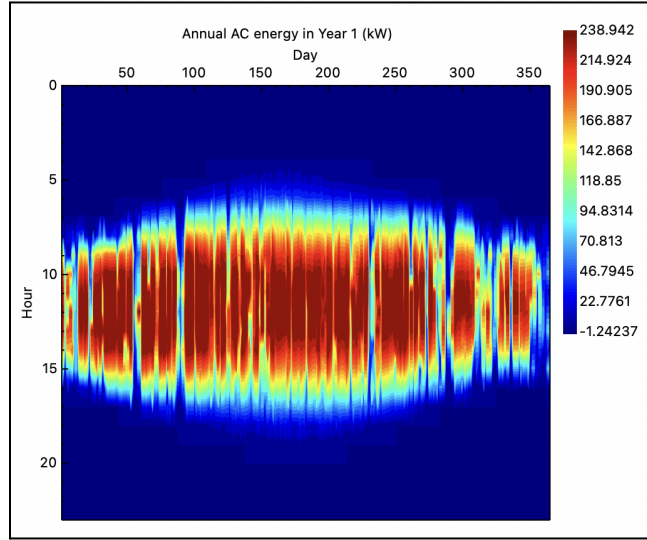


Figure 7: SAM model of annual AC energy in 1 year

The Figure 7 above shows a SAM model of the energy output of the solar farm designed near the Coon Rapids dam site. The farm is small-scale and covers approximately 1500 m². The peak power occurs around noon, reaching 238 kW due to the higher solar irradiance during this time. The addition of a solar farm improves overall energy production, reliability, and flexibility of the design. The solar farm will be non-isolated, meaning there is no galvanic isolation and a direct connection between the modules and the grid. A non-isolated system allows for simplicity and robustness, which is required in a small-scale solar farm. The design will also use a single-stage converter, as shown in Figure 8 below. The grid link will consist of an LCL filter, which helps remove high-frequency switching from the inverter. The grid-side converter (GSC) is the main control of the system and uses current and voltage sensors to track and maintain the maximum power point (MPP).

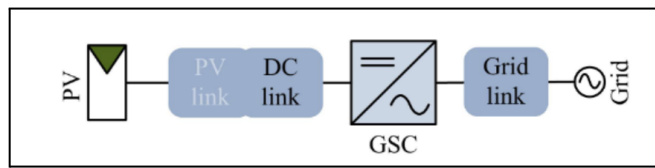


Figure 8: Single stage converter diagram of solar farm

The most important part of any solar energy system is maximum power point tracking (MPPT). As the solar irradiance and temperature of the photovoltaic cells change, the maximum power that can be obtained also changes. This requires an algorithm that continuously adjusts the operating voltage and current to maintain an efficient system. For the small-scale system, the hill climbing algorithm is used. This method varies the duty cycle of the inverter to locate the maximum power point based on feedback from voltage and current sensors. This can be seen in Figure 9 below, which illustrates how the algorithm converges to the maximum power output by adjusting the operating voltage.

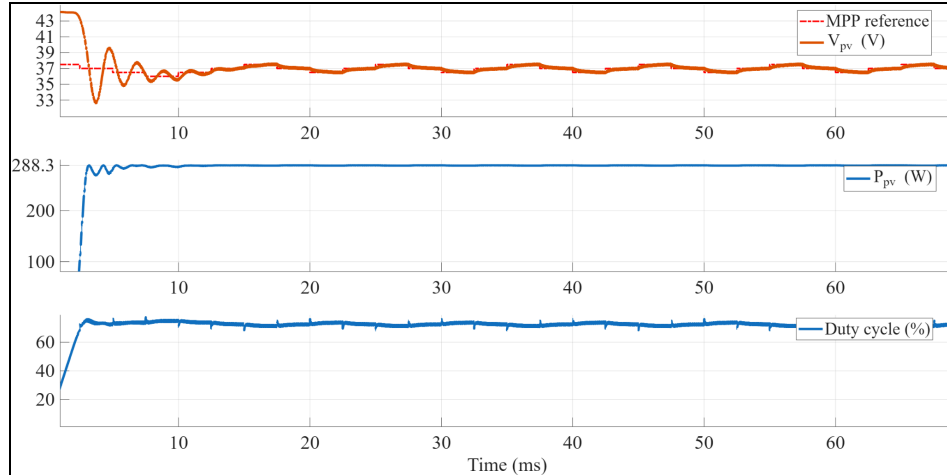


Figure 9: Hill climbing MPPT algorithm MATLAB simulation

Figure 9 above shows how the MPPT algorithm would perform in our system. The graphs show how the algorithm adjusts the operating point by varying the duty cycle which controls the output voltage and tracks the maximum power point under given conditions. As the algorithm iterates, it moves toward the peak of the power curve and stabilizes near the maximum value, demonstrating its ability to efficiently extract power from the photovoltaic array. Small oscillations around the peak can be observed, which are expected due to the nature of the hill climbing method. Overall, the results confirm that the algorithm is effective in tracking and maintaining operation near the maximum power point.

The annual energy generation of the proposed system was evaluated using both hydropower modeling and solar resource data. The hydropower system, based on historical USGS discharge data and a 5-unit turbine configuration, produces approximately 12,700 MWh annually, corresponding to a capacity factor of about 67%. This indicates there is strong utilization of available river flow and consistent base-load generation throughout the year.

Monthly hydropower production exhibits clear seasonal variation, with peak generation occurring during late spring and early summer, where output exceeds 1,500 MWh per month. In contrast, winter months experience reduced generation, with output ranging from 400-600 MWh per month due to lower flow conditions. This behavior is characteristic of run-of-river systems and reflects natural variability over river discharge.

The solar component contributes to approximately 380-400 MWh annually, providing additional energy during daylight hours and peaking in summer months at approximately 45-50 MWh per month. Although solar represents a smaller fraction of total annual generation, it enhances the overall system performance by increasing daytime output and supplementing seasonal hydropower variability.

The combined hybrid system yields a total annual energy production of approximately 13,000 MWh, demonstrating the effectiveness of integrating solar with a run-of-river hydro system. Hydropower serves as the primary energy source, delivering reliable and continuous generation, while solar contributes incremental energy that improves overall system efficiency and utilization of renewable resources.

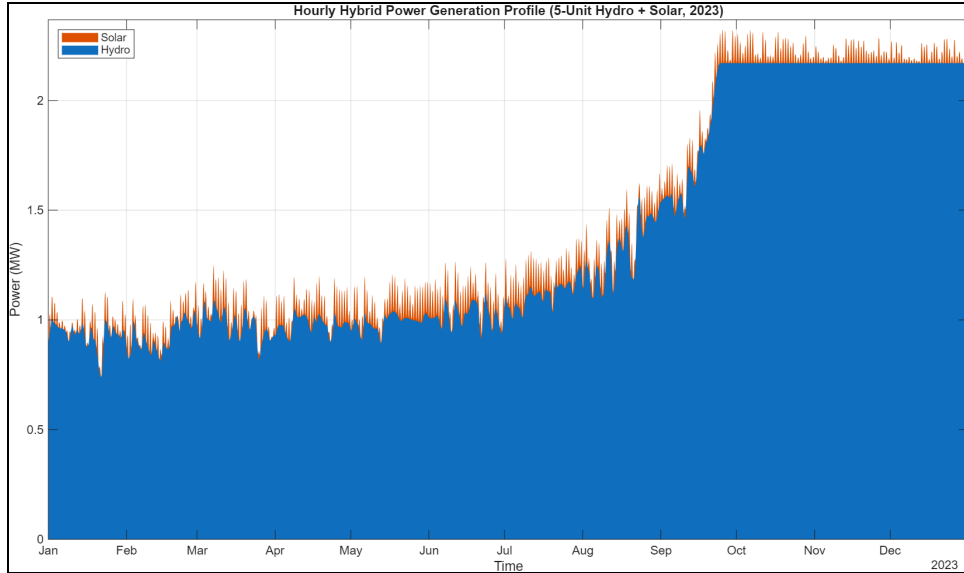


Figure 10: Hybrid Hourly Generation Profile

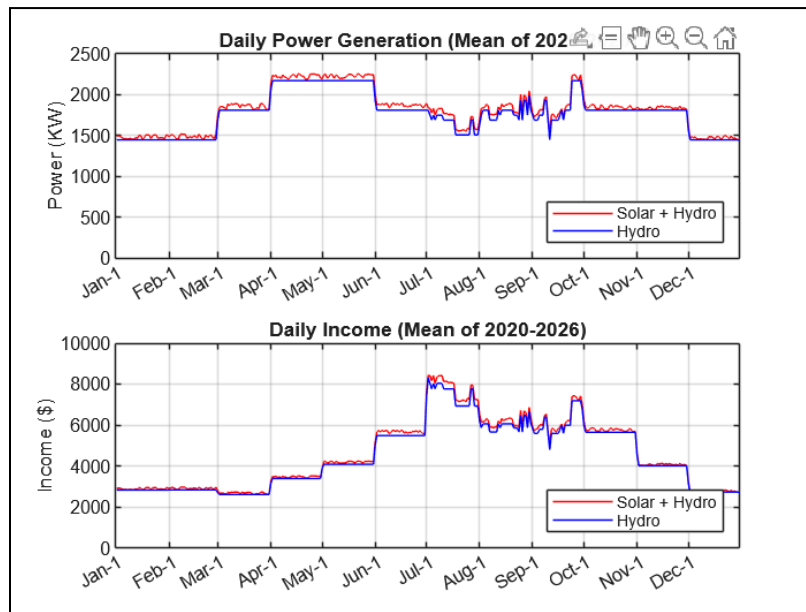


Figure 11: Annual Energy Output & Income

Figure 11 shows what we estimate the annual power output & revenue generated by the dam. More specifically, it displays the mean data of 6 years of simulation (2020-2026) using real world flow data at Coon Rapids. Additionally, it shows both outputs with the inclusion of energy generated by the solar co-development.

Table 2: Hybrid Power Generation Components

	Hydro	Solar	Overall
Generation (MWh)	12,699	480	13,479
Average Output (MW)	1.45	.047	1.497
Capacity Factor	67%	15.5%	61.9%
LCOE (¢/kWh)	7.961	12.16	8.11

2.2 Feasibility Assessment

Feasibility is primarily influenced by the ability to integrate turbine modules within the existing structure of Coon Rapids Dam without compromising safety or operation. The design is more constrained by regulatory and structural factors rather than hydraulic limitations. The introduction of localized penetrations requires careful consideration of load paths and structural integrity, with reinforced openings and controlled spacing used to reduce stress concentrations. Full implementation would require detailed structural validation to ensure that modifications do not negatively impact dam performance.

From a hydraulic standpoint, the system is feasible under low-head conditions typical of small hydropower applications [5]. Consistent upstream water levels and controlled diversion through guided intake geometry allow the system to operate within a stable range while accommodating variations in flow and environmental constraints. This directly supports the selection of the StreamDiver turbine, which is specifically designed for efficient operation in low-head, high-flow environments.

Feasibility is constrained more by regulatory and structural factors than by hydraulic limitations. Previous hydropower development efforts at the site were not completed due to permitting complexity, highlighting the importance of minimizing structural modification and operational interference. However, stakeholder input indicates that development remains viable if these concerns are addressed. The modular approach supports this by enabling phased installation and reducing overall impact. These results indicate that feasibility is driven more by integration constraints than by hydraulic limitations, reinforcing the importance of a modular, low-impact design that aligns with site constraints.

2.3 Optimization

Optimization strategies focused on balancing hydraulic performance, structural limitations, and system scalability. Intake geometry and flow passage dimensions were selected to promote smooth redirection and minimize energy losses, consistent with established small hydropower design principles [5].

At the system level, distributing flow across multiple modules was found to provide more consistent performance than concentrating flow through a single unit. At a system level, distributing flows across multiple modular turbine units improves performance under variable flow conditions by allowing individual units to operate closer to their peak efficiency. This modular approach gives greater operational flexibility, maintains higher efficiency across a wider range of discharges, and improves system reliability compared to a single large turbine operating under off-design conditions. This configuration allows operation within site constraints while limiting the size and impact of individual penetrations, improving both structural feasibility and operational flexibility.

Performance modeling was used to evaluate system behavior across a range of flow conditions. The

resulting power duration curve (Figure 12) shows that the system maintains consistent output over a significant portion of operating conditions, ranging from 1.3-3.04 MW supporting the selection of a distributed modular configuration rather than a single high-capacity unit. This behavior demonstrates that increasing the number of turbine units beyond the selected configuration results in diminishing returns. Increasing from 3 to 7 units increased installed capacity by 133%, but annual energy only increased by about 48%, furthermore capacity factor dropped about 37% and LCOE increased by about 58%, supporting the decision to implement five turbines.

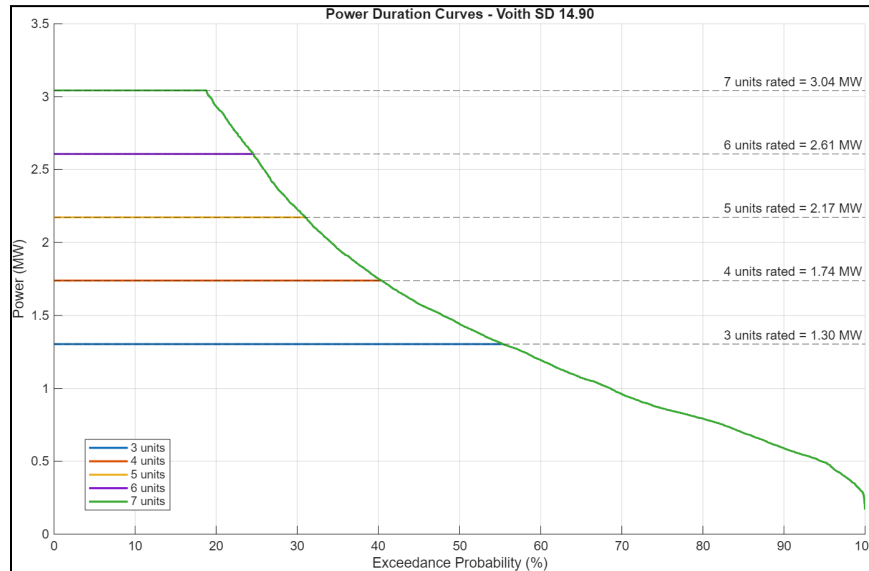


Figure 12: System Power duration curve showing system output across varying flow conditions

Tradeoffs were evaluated between increasing the number of turbine units and the associated structural modification and cost. While additional modules increase total power output, they also require more penetrations and installation effort resulting in lower economic outputs. The selected configuration of 5 units operates at peak capacity for about 31% of the time compared to 19% for 7 units. The selected configuration represents a balance between energy capture, constructability, and economic feasibility, ensuring that the system remains practical for implementation at Coon Rapids Dam.

2.4 Engineering Analysis

Engineering analysis was conducted to estimate the performance of the system under site-specific conditions at Coon Rapids Dam. Power output was evaluated using standard hydropower relationships [4], including $P = \rho g Q H \eta$ and $P = T \omega$, relating hydraulic input to mechanical output. These equations provided the foundation for estimating system performance and guiding turbine design decisions. The analysis assumes steady-state flow conditions, constant turbine efficiency, negligible head losses outside of intake geometry, and uniform flow distribution across turbine modules. These assumptions simplify system behavior while capturing the dominant performance characteristics of the turbine system.

A MATLAB-based turbomachinery model was developed to analyze system behavior across a range of operating conditions. Inputs included a net head of approximately 5.21 m and a controlled flow rate of 10 m³/s, with a rotational speed sweep from 20 to 300 RPM. Efficiency assumptions were incorporated to

account for hydraulic and mechanical losses, allowing for realistic performance estimation.

The resulting analysis produced torque and power relationships as a function of rotational speed. As shown in Figure 13, shaft torque decreases with increasing runner speed, which defines a feasible operating region. The model indicates an effective operating point near 120 RPM, which represents a balance between torque and rotational speed, enabling efficient power generation without exceeding mechanical or hydraulic limits.

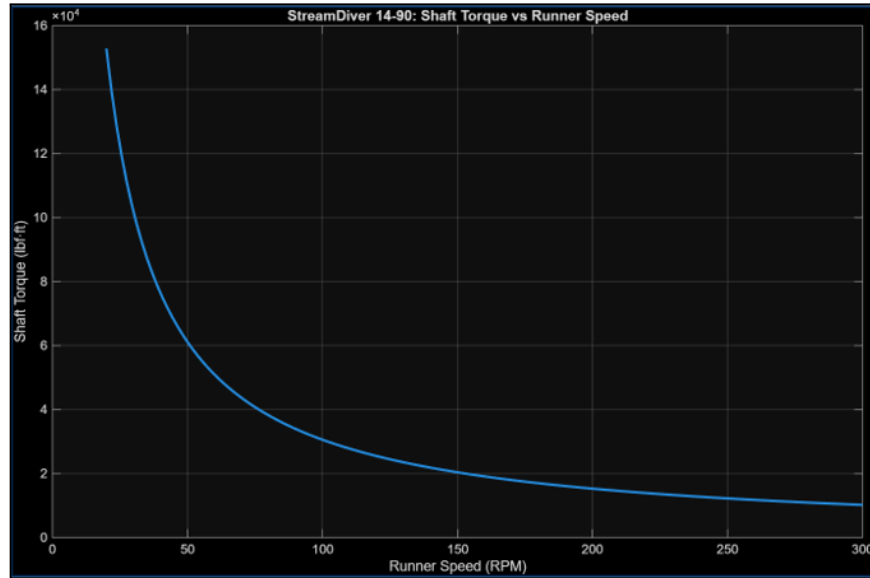


Figure 13: Shaft Torque vs. Runner Speed for the turbine system

Overall, the engineering analysis demonstrates that the StreamDiver system can operate within a stable and predictable performance range under site conditions. These results directly inform turbine sizing and system configuration, ensuring that the selected design operates within a feasible and efficient performance range under expected site conditions.

2.5 Economic Analysis

Economic feasibility was evaluated using the levelized cost of energy (LCOE), which represents the cost per unit of electricity generated over the system lifetime [8].

Cost estimates were derived using outputs from the JEDI model, including capital expenditures (CAPEX) of approximately \$10.5 million and annual operational expenditures (OPEX) of approximately \$313,000 per year. These values were used in conjunction with projected energy production to evaluate overall system cost effectiveness through LCOE. For the selected configuration of five turbine modules, the system achieves a capacity of approximately 2.17 MW and generates 12,699 MWh annually, corresponding to a capacity factor of 67%.

Table 3: Summary of Economic Results for turbine system

Units	Capacity	Energy	CF	CAPEX	OPEX	LCOE
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		(MWh/yr)				(\$/MWh)
5	2.17	12,699	67%	\$10.5 Million	\$313,000/yr	\$79.61

CAPEX represents the dominant cost driver, with structural integration and turbine installation accounting for the majority of total project cost, while OPEX remains relatively low due to minimal ongoing operational requirements.

The resulting LCOE for the system is approximately \$79.61/MWh, which aligns with the project target of \$80.00/MWh, indicating that the system meets its economic design objective. This value is consistent with the expected range for small hydropower installations [9], reflecting the additional costs associated with structural integration and modular deployment. This value is competitive within the small hydropower sector, where LCOE typically ranges from \$60 to \$120/MWh, supporting the economic viability of the proposed system.

Economic performance is sensitive to the number of turbine modules. Increasing the number of turbines improves total energy output but results in higher capital costs due to additional structural modification. This tradeoff demonstrates that increasing turbine count beyond the selected configuration results in diminishing economic returns, reinforcing the selection of five turbines as the optimal balance between energy production and capital cost. This economic behavior directly supports the system configuration selected in Section 2.3, linking cost performance to design optimization.

To conceptualize the system's total energy output, the annual generation of 13,479 MWh was compared to the average residential electricity consumption in Minnesota [12]. Based on average household usage of 712 kWh per month (8,544 kWh annually), the proposed hydropower system is capable of supplying energy to approximately 1,550 homes per year as shown in Table 4.

Table 4: Energy Production and Residential Impact

Parameter	Installed Capacity (MW)	Capacity Factor (%)	Annual Energy Production (MWh/yr)	Annual Energy Production (kWh/yr)	Avg. MN Household Consumption (kWh/yr)	Equivalent homes Powered
Hydro	2.17	67	12,699	12,699,000	8,544	1,490
Solar	.25	15.5	480	480,000	8,544	56
Hybrid	2.42	61.9	13,479	13,479,000	8,544	1,546

This comparison provides a practical measure of system impact, demonstrating that the proposed design can supply energy to approximately 1,550 homes annually while maintaining a relatively small environmental footprint.

2.6 Testing & Validation

A scaled prototype of the StreamDiver turbine was constructed and tested to evaluate system performance under controlled conditions and to validate trends predicted by the turbomachinery model. The purpose of testing was not to replicate full-scale performance, but to observe how key variables, specifically flow velocity, applied load, rotational speed, and torque, interact within the system. This approach provides insight into real-world behavior and supports the validity of the analytical model. The testing is meant to validate performance trends predicted by the analytical model rather than to replicate full-scale system

behavior.

Testing was conducted using a recirculating flow setup in combination with a Prony brake system to apply controlled resistance to the turbine shaft. Three distinct flow conditions were tested, along with multiple loading scenarios including two applied dead weights and an unloaded case. Torque was determined using a force gauge and a known lever arm, while rotational speed was measured with a tachometer. These measurements allowed for direct observation of the relationship between torque, rotational speed, and applied load across varying flow conditions.

Table 5: Testing Results

Weights: [g]	Main (N)	Dead Weight (N)	force (N)	rmp	w (rad/s)	Torque	W (power)	Efficiency	Volume(L)	Time (s)	flow rate(L/s)
0	0	0	0	4000	418.879	0	0	0%	5	5.47	0.914076782
20	0.65	0.1962	0.4538	3500	366.519	0.01475	5.405607579	24%	5	5.48	0.912408759
40	1.5	0.3924	1.1076	1000	104.72	0.036	3.769597025	17%	5	5.85	0.854700855
										Average L/s	0.893728799
Weights: [g]	Main (N)	Dead Weight (N)	force (N)	rmp	w (rad/s)	Torque	W (power)	Efficiency	Volume(L)	Time (s)	flow rate(L/s)
0	0	0	0	2400	251.327	0	0	0%	5	8.49	0.588928151
20	0.45	0.1962	0.2538	1500	157.08	0.00825	1.29567135	21%	5	8.81	0.56753689
40	0.6	0.3924	0.2076	0	0	0.00675	0	0%	5	8.54	0.585480094
										Average L/s	0.580648378
Weights: [g]	Main (N)	Dead Weight (N)	force (N)	rmp	w (rad/s)	Torque	W (power)	Efficiency	Volume(L)	Time (s)	flow rate(L/s)
0	0	0	0	840	87.9646	0	0	0%	5	12.76	0.39184953
20	0.3	0.1962	0.1038	200	20.944	0.00337	0.070654419	4%	5	12.45	0.401606426
40	0.45	0.3924	0.0576	0	0	0.00187	0	0%	5	12.58	0.39745628
										Average L/s	0.396970745

Although the prototype does not maintain geometric or dynamic similarity with the full-scale system, the results provide meaningful insight into performance trends. While the direct results cannot be multiplied by its scale (~30) to collect a real world output value, understanding generally how the turbine will react under certain conditions and if power can be generated was accomplished. As flow velocity increased, both torque and rotational speed increased, resulting in higher overall power output. However, excessive loading reduced rotational speed significantly, while minimal loading limited torque generation. These observations indicate that optimal performance occurs within a moderate operating range where torque and rotational speed are balanced.

The experimental results align with trends predicted by the MATLAB turbomachinery model, particularly in demonstrating the inverse relationship between torque and rotational speed and identifying a stable operating region. This behavior is consistent with the results presented in Section 2.4, where as rotational speed increases, torque decreases. This is validated by the testing, shown in table 5, where as the rotational speed slows, more torque is provided to the system. While absolute performance values cannot be directly scaled to full-scale conditions, the experimental results reliably capture key trends, including the relationship between torque, rotational speed, and flow rate.

Overall, testing confirms that the selected turbine configuration operates within a predictable and stable performance range under varying conditions. Limitations of the testing include scale effects, simplified flow conditions, and the inability to fully replicate field hydraulic variability. These findings reinforce the feasibility of the design and demonstrate that system performance is governed by maintaining a balanced operating range rather than maximizing a single parameter. Overall, the testing results support the feasibility of the proposed design by confirming expected performance behavior under controlled conditions.

2.7 Environmental & Regulatory Considerations

The proposed hydropower retrofit at the Coon Rapids dam involves the installation of internally drilled intake structures, significantly reducing the external footprint of the project. As a result, the project falls under federal, state, and local environmental regulations, with primary oversight from the Federal Energy Regulatory Commission (FERC), the Minnesota Department of Natural Resources, and compliance with the National Environmental Policy Act (NEPA). Because the design retrofits an existing non-powered dam without significantly altering the river's hydraulic profile or adding major external infrastructure, the project is well positioned for a streamlined regulatory pathway, such as a small hydropower exemption or expedited licensing process through FERC.

Although the system does not actively divert water from the main river channel, it intercepts a portion of flow. The turbine system is designed to use approximately 15% of the total river discharge, ensuring that about 85% remains in the main channel. This limited diversion still requires MN DNR permitting as a non-consumptive appropriation, but the small fraction minimizes environmental impact and supports regulatory approval.

Under NEPA, the limited scope and reduced surface disturbance of the internal drilled configuration support a lower level environmental review, such as an Environmental Assessment(EA), rather than a full Environmental Impact Statement. The absence of large external structures, new impoundments, or major flow alterations minimizes impacts to surrounding land use, visual aesthetics, and recreational access. Which is critical given the dam's location within a recreational park.

At the state level, MN DNR regulations emphasize protecting aquatic ecosystems, maintaining water quality, and preserving fish passage and habitat integrity. While the internal design reduces shoreline and surface disturbance, it introduces local hydraulic effects at the intake openings. Concentrated flow into these intake ports can create higher approach velocities, increasing the risk of fish entrainment. To mitigate this, the design incorporates fish friendly features including screening systems, reduced approach velocities, and optimized intake geometry.

Water quality impacts must also be evaluated, particularly with respect to dissolved oxygen levels, temperature stratification, and sediment transport. Because the proposed design is run-of-river and does not significantly alter storage or flow regime, impacts are expected to be negligible.. Additionally, the project must comply with Section 401 water quality certification requirements under the Clean Water Act [16].

A key consideration unique to the internal drilled approach is structural integrity. Core drilling and installation of intake conduits introduce penetrations within the dam body, which must be carefully engineered to prevent cracking, seepage, or long term degradation. Structural analysis and coordination with dam safety authorities ensure stability through proper sealing, grouting.

Construction impacts for the internal design are significantly reduced compared to traditional external hydropower installations. Instead of large-scale cofferdams and extensive excavation, construction is limited to localized drilling operations, equipment placement, and turbine installation. This reduces turbidity, habitat disturbance, and construction time, with best management practices further mitigating impacts.

Recreational and aesthetic considerations are especially important at Coon Rapids, the design prioritizes a low visual profile by integrating turbine modules within or adjacent to existing infrastructure, avoiding

large external powerhouse additions. Public access and minimal disruption remain key design constraints.

By leveraging existing infrastructure and minimizing flow diversion, the design balances power generation, regulatory feasibility, and environmental protection, making it well suited for development in recreationally sensitive settings.

2.8 Merits & Weaknesses

The proposed system offers several advantages as a modular hydropower solution integrated into existing dam infrastructure. A primary merit of the design is its ability to generate power without requiring large-scale reconstruction or new dam construction. By utilizing localized penetrations and controlled flow diversion, the system enables energy extraction while maintaining overall dam operation. The modular configuration further enhances this approach by allowing scalable deployment, phased installation, and flexibility in adapting to site specific constraints. Additionally, the system demonstrates strong performance consistency, as indicated by the engineering analysis and power duration curve, supporting reliable energy generation across a range of flow conditions.

Another key advantage is the system’s alignment with existing infrastructure and site conditions. By distributing turbine units along the structure, the design reduces reliance on a single operating point and allows for more efficient use of available flow. The integration of guided intake geometry also improves hydraulic performance by minimizing flow separation and energy losses. Combined with a strong capacity factor and alignment with defined economic targets, these features support the overall feasibility of the system.

However, the design also presents several limitations. The requirement for structural penetrations introduces engineering challenges and potential risk to dam integrity, necessitating detailed structural analysis and validation prior to implementation. Regulatory and permitting complexity remains a significant barrier, particularly given past challenges at the site. Additionally, while the modular design improves flexibility, it increases installation complexity and total capital cost due to the need for multiple turbine units and associated structural modifications.

Overall, the StreamDiver system represents a balanced tradeoff between performance, feasibility, and implementation complexity. While structural and regulatory challenges must be addressed, the system’s modularity, adaptability, and demonstrated performance provide a strong foundation for further development.

2.9 Risk Identification & Mitigation

A range of technical, environmental, regulatory, and economic risks must be considered for successful implementation at Coon Rapids Dam. These risks were identified based on site-specific constraints, system design requirements, and stakeholder input. Each risk was evaluated using a qualitative scoring system based on probability of occurrence and potential impact, allowing for prioritization of the most critical factors affecting overall feasibility.

Table 6: Risk Identification and Mitigation Matrix

#	Risk	Description	Probability (1-5)	Impact Description	Impact (1-5)	RISK SCORE (Pxl)	Mitigation Strategy
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1	Structural Modification	Penetrations required within dam structure	3	Potential compromise of structural integrity and safety	5	15	Limit size/spacing, structural analysis, reinforcement design
2	Installation complexity	Construction within existing dam environment	3	Increased construction difficulty, time, and cost	3	9	Phased installation, use existing access points
3	Permitting / approval	Complex regulatory requirements and approvals	4	Project delays or inability to proceed	4	16	Early coordination with agencies, minimize modification scope
4	Fish barrier interference	Dam functions as invasive species barrier	4	Disruption of ecological control measures	5	20	Maintain flow paths, limit diversion, coordinate with DNR
5	Flow diversion limits	Restrictions on allowable diverted flow	3	Reduced power generation potential	4	12	Optimize diversion ratio, operate within constraints
6	CAPEX uncertainty	Uncertainty in structural and installation costs	3	Increased project cost and reduced economic viability	4	12	Sensitivity analysis, modular deployment
7	Maintenance / debris / icing	Debris accumulation or seasonal icing	2	Reduced performance or operational downtime	3	6	Trash racks, maintenance planning, accessible design

As shown in Table 6, the highest risks are associated with structural modification, regulatory approval, and environmental constraints. The requirement for localized penetrations within the dam presents a significant technical challenge, as maintaining structural integrity is essential for safe operation. Regulatory complexity introduces additional uncertainty, particularly given the history of previous hydropower development efforts at the site. Environmental considerations, including preservation of the dam’s function as a fish barrier, further limit allowable system operation.

Mitigation strategies focus on reducing both likelihood and impact through design and planning decisions. Structural risks are addressed through reinforcement and controlled penetration design. Regulatory risks are mitigated through early coordination with governing agencies, while environmental risks are managed by maintaining controlled flow diversion.

2.10 Design Takeaways

The design process highlighted several key insights related to system performance, feasibility, and implementation:

- Quantitative analysis of flow characteristics and duration proved critical in determining optimal system sizing, as oversizing leads to underutilization and diminishing returns

- Modular system design enables scalable deployment while minimizing structural impact, making it well-suited for retrofitting existing dam infrastructure
- Economic feasibility is highly sensitive to turbine count, reinforcing the need to balance energy production with capital cost rather than maximizing output alone
- System feasibility is constrained more by regulatory and structural considerations than by hydraulic limitations, emphasizing the importance of early stakeholder engagement
- Experimental testing validated key performance trends and confirmed the reliability of the analytical model within a realistic operating range

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