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Extracting Power from Libya's Great Man-Made River using Python, Lucid Turbine, and Hydro XS

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استخراج الطاقة من النهر الصناعي العظيم في ليبيا باستخدام بايثون ولوسيد توربين وهيدرو اكس اس

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Abstract:
This paper investigates the potential for sustainable energy generation within Libya's Great Man-Made River (GMMR) Project through the integration of in-pipe hydrokinetic turbines, specifically focusing on a comparative analysis of Lucid Energy's LucidPipe Power System and Hydro XS Turbines. The GMMR, a monumental civil engineering endeavor, transports vast quantities of water across Libya, presenting a unique opportunity for harnessing untapped energy from its extensive pipeline network. Utilizing Python-based simulation, this study models the energy recovery potential by integrating these turbines within the GMMR infrastructure. For the LucidPipe system, a conical nozzle is incorporated to regulate and increase velocity or pressure, while the Hydro XS Turbines are evaluated for direct integration. The simulation incorporates fluid dynamics principles, including head loss calculations due to friction and minor losses, and evaluates electrical power output under a specified GMMR pipe water velocity of 0.95 m/s and realistic pressure assumptions derived from GMMR operational data. The findings demonstrate significant energy generation capabilities for both technologies, highlighting their feasibility and environmental benefits in augmenting Libya's energy supply while maintaining the primary function of water delivery. This research provides a foundational analysis for future detailed engineering and economic assessments of such systems within the GMMR infrastructure.

Keywords: Great Man-Made River, Hydrokinetic Turbines, In-pipe Energy Recovery, Renewable Energy in Libya.

الملخص:
تتناول هذه الورقة البحثية إمكانية توليد الطاقة المستدامة داخل مشروع النهر الصناعي العظيم في ليبيا من خلال دمج توربينات هيدروكينتيكية داخل الأنابيب، مع التركيز بشكل خاص على التحليل المقارن بين نظام "لوسيد بايب" للطاقة من شركة Lucid Energy وتوربينات Hydro XS. يُعد النهر الصناعي العظيم مشروعاً هندسياً مدنياً ضخماً ينقل كميات هائلة من المياه عبر ليبيا، مما يوفّر فرصة فريدة لاستغلال الطاقة غير المستغلة من خلال شبكة الأنابيب الواسعة التابعة له. يعتمد هذا البحث على محاكاة باستخدام لغة Python لنمذجة إمكانية استرجاع الطاقة من خلال دمج هذه التوربينات ضمن بنية النهر الصناعي. في نظام LucidPipe، يتم تضمين فوهة مخروطية لتنظيم وزيادة السرعة أو الضغط، بينما تُقيَّم توربينات Hydro XS من حيث إمكانية دمجها المباشر في النظام. تتضمن المحاكاة تطبيق مبادئ ديناميكا الموائع، بما في ذلك حسابات الفقد في الارتفاع (Head Loss) نتيجة الاحتكاك والخسائر الثانوية، كما يتم تقييم الطاقة الكهربائية المنتجة تحت سرعة مياه أنبوب النهر الصناعي المقدرة بـ 0.95 م/ث، وافتراضات ضغط واقعية مستمدة من بيانات

التشغيل الفعلية للنهر الصناعي. وتُظهر النتائج قدرة كبيرة على توليد الطاقة لكلا التقنيتين، مما يبرز جدواهما وفوائدهما البيئية في دعم إمدادات الطاقة في ليبيا دون التأثير على الوظيفة الأساسية للمشروع وهي نقل المياه. ويقدم هذا البحث تحليلاً أولياً يُمهّد لإجراء تقييمات هندسية واقتصادية مفصلة في المستقبل حول دمج هذه الأنظمة ضمن بنية النهر الصناعي.

الكلمات المفتاحية: النهر الصناعي العظيم، التوربينات الهيدروكينتيكية، استرداد الطاقة من الأنابيب، الطاقة المتجددة في ليبيا.

Introduction

The escalating global demand for energy, coupled with the imperative to transition towards sustainable and renewable sources, has spurred innovation in various domains of power generation. Hydropower, a well-established renewable energy technology, traditionally relies on large-scale dams and reservoirs [1]. However, a less conventional yet increasingly promising avenue lies in harnessing energy from existing water infrastructure, such as municipal water pipelines and large-scale water transfer projects. These systems, designed primarily for water conveyance, often possess significant hydraulic head and continuous flow, representing a substantial, often overlooked, energy resource.

Libya's Great Man-Made River (GMMR) Project stands as a testament to human ingenuity in overcoming geographical and environmental challenges to secure vital resources. Conceived in the late 1960s and initiated in 1984, the GMMR is an extensive network of pipelines transporting fresh water from the ancient Nubian Sandstone Aquifer System in the Sahara Desert to the populous coastal regions of Libya [2]. Described as the world's largest irrigation project, it comprises over 2,820 kilometers of underground pipes, with diameters reaching up to 4 meters, and supplies approximately 6.5 million cubic meters of water daily [3]. While its primary objective is water supply for agricultural and domestic use, the sheer scale and continuous flow within its pipeline system present a compelling opportunity for integrated energy recovery.

In parallel, advancements in hydrokinetic turbine technology have led to the development of in-pipe systems capable of generating electricity without disrupting water flow or requiring significant civil works. Lucid Energy's LucidPipe Power System is a notable example, designed to operate within large-diameter pipelines (24-96 inches, or approximately 0.61 to 2.44 meters) and convert the kinetic energy of flowing water into clean electricity [4]. These turbines are engineered for minimal head loss and are suitable for integration into existing infrastructure, making them an attractive solution for decentralized power generation.

This research explores the theoretical and practical feasibility of integrating Lucid Energy's LucidPipe Power System and Hydro XS Turbines within the GMMR infrastructure to generate electricity. Specifically, it investigates the energy recovery potential by modeling the installation of these turbines within a reducer section, transitioning from the GMMR's characteristic 4-meter pipe diameter to a diameter compatible with LucidPipe turbines and Hydro XS Turbines [5-7]. Through a Python-based simulation, to analyze the hydraulic and electrical performance of such a system under various flow conditions and realistic pressure parameters derived from the GMMR's operational characteristics. The objective is to quantify the potential electrical power output, assess the hydraulic implications, and provide a preliminary evaluation of this innovative approach to sustainable energy generation in the context of one of the world's largest water transfer projects. This study aims to contribute to the growing body of knowledge on hydropower recovery from existing infrastructure and offer insights into diversifying Libya's energy portfolio.

Lucid Energy In-Pipe Turbines

Lucid Energy (often referred to for its "LucidPipe" system) develops in-pipe hydrokinetic turbines that generate electricity from flowing water in gravity-fed pipelines [8]. Lucid Energy's LucidPipe Power System represents a cutting-edge solution for generating clean electricity from existing water infrastructure. Unlike traditional hydropower systems that require significant civil construction and can disrupt ecosystems, LucidPipe turbines are designed for in-conduit installation, meaning they operate directly within large-diameter pipelines [9,10]. This design allows for energy recovery without altering the primary function of the water pipeline or impacting water quality.

Lucid Turbines their specifications: Water Velocity and kW Output

Water Velocity:

- Optimal Performance: LucidPipe™ turbines achieve their best performance and reliability at water velocities greater than 4 ft/s (approximately 1.2 m/s).
- Typical Operating Range: Typical water velocities in pipelines where LucidPipe™ systems are installed range from 4-7 ft/s (1.7-2.1 m/s).
- Cut-in Speed: While not explicitly stated as a single value across all literature, the system is designed to generate power across a very wide range of flow conditions and velocities. Other

research on similar in-pipe hydrokinetic turbines indicates cut-in speeds typically around 0.9 m/s.

- Rated Flow/Cut-out Speed: The LucidPipe™ system is designed for broad operational flexibility. Rated flow details are often provided in relation to power output for specific pipe diameters.

kW Output:

LucidPipe™ systems are designed to be modular, with power output varying depending on the pipeline diameter, water velocity, and the number of turbines installed.

- Individual Turbine Output:
  - A 24-inch (600mm) diameter LucidPipe™ turbine can produce around 14 kW.
  - A 42-inch (1000mm) diameter turbine can produce around 50 kW.
  - A 60-inch (1500mm) diameter turbine can produce up to 100 kW.
- System Output: Multiple turbines can be installed in a single pipeline to increase overall power generation. For example:
  - A system with four 42-inch turbines can generate a total of 200 kW.
  - Other installations include multi-turbine systems designed for specific total outputs, such as a 60-kW system.

Key Characteristics of LucidPipe™ Technology:

- In-pipe Hydrokinetic: The turbines are installed directly inside existing large-diameter water pipelines, harnessing the kinetic energy of the flowing water.
- Minimal Head Pressure Extraction: The system is designed to extract very little head pressure (typically 1-6 PSI or 1-4 meters) to avoid impacting the normal flow and operation of the pipeline.
- Lift-Based, Vertical Axis Spherical Turbine: LucidPipe™ utilizes a unique spherical turbine design that generates power through lift forces as water flows through it.
- Scalable and Modular: The system can be scaled to various pipeline sizes and power requirements by installing multiple turbines.

HydroXS® Energy Recovery System

by InPipe Energy is another innovative solution for generating renewable energy from flowing water within pipelines. Similar to LucidPipe, it focuses on recovering "wasted" energy from excess pressure in water distribution systems.

HydroXS® Energy Recovery System their specifications: Water Velocity and kW Output

Unlike traditional hydropower which relies on significant "head" (vertical drop), the HydroXS® system is a micro-hydro turbine designed for **in-pipe pressure management and energy recovery**. This means its primary operational parameters are related to *differential pressure* and *flow rate*, rather than solely water velocity. However, velocity is inherently linked to flow rate within a given pipe diameter.

Water Velocity/Flow Rate:

- Operating Conditions: The HydroXS® system is designed to operate in pipelines with consistent flow and differential pressure.
- Adaptability: A key feature of the HydroXS® is its variable speed micro-turbine technology. This allows it to adjust the turbine speed to efficiently generate energy while precisely maintaining downstream water pressure, even as conditions change. This means it can maintain efficiency over a wider range of flow rates and pressures compared to fixed-speed micro-hydro turbines.
- Typical Applications: It's used in potable water distribution systems, wastewater facilities, and industrial factories where there's available differential pressure.

kW Output:

The power output of a HydroXS® system is highly dependent on the available differential pressure (DeltaP) and the flow rate (Q) through the pipe. The power generated is generally proportional to the product of these two factors.

- System Sizing: HydroXS® is available in a wide range of pipe sizes, from 2-inch to 110-inch (51 mm – 2.4 meters). This indicates a scalable power output depending on the application.
- Potential Energy Recovery: Instead of "burning off" differential pressure with control valves, HydroXS® converts this otherwise wasted pressure into renewable energy.
- Example Applications: While specific kW figures for individual units aren't as readily published as a simple lookup table, the system is designed to provide significant energy savings and can help water utilities become carbon neutral. One reported application involved powering a stadium in Oregon by converting excess water pressure into electricity. Given its application in pressure management, the output can range from a few kilowatts for smaller systems to potentially tens or hundreds of kilowatts for larger installations with significant pressure differentials and flow rates.

Key Characteristics of HydroXS® Technology:

- In-pipe Energy Recovery: Integrates directly into existing pipelines to convert excess water pressure into electricity.
- Smart Control Technology: Features state-of-the-art control valve technology integrated with a micro-turbine and a regenerative variable frequency drive (VFD) with sensors connected to a PLC-based control system. This enables precise pressure management and maximizes energy generation.
- Variable Speed Operation: Unlike many traditional micro-hydro turbines, the HydroXS® can operate efficiently across multiple flow and pressure conditions by adjusting its speed.
- Turnkey System: Offered as a standardized, pre-assembled, and tested product, providing a superior alternative to custom-designed micro-hydro solutions or conventional control valves for pressure reduction.
- Real-time Data: Provides real-time data with an interactive dashboard and is SCADA-compatible.
- Applications: Ideal for potable water distribution, wastewater, and industrial settings with consistent flow and differential pressure.

Material and Methods

Python for Hydrokinetic Energy Simulation

Python was selected for this hydrokinetic turbine simulation due to its robust capabilities in scientific computing and fluid dynamics modeling. As an open-source, high-level programming language, Python enabled the implementation of key hydraulic equations, including Bernoulli's principle and the Darcy-Weisbach friction loss model, to quantify turbine performance under the Great Man-Made River Project's operational conditions (0.95 m/s flow in 4 m pipes). Libraries such as NumPy efficiently handled array-based calculations for Reynolds numbers and head losses, while Matplotlib generated publication-ready 2D/3D visualizations of power curves and turbine geometries.

Key strengths:

- Open-source accessibility vs. costly alternatives (e.g., MATLAB)
- Seamless integration of hydraulic theory with numerical methods
- Scalability from single-turbine analysis to system-wide deployment studies

System designed Overview

The study evaluates the performance of two hydrokinetic turbine systems Lucid Turbines with a conical nozzle, and Hydro XS in-pipe turbines within the context of the Great Man-Made River (GMMR) Project in Libya. The GMMR operates with a pipe diameter of 4.0 m, and a water velocity of 0.95 m/s, providing a baseline for energy extraction potential.

Turbine Configurations

- **Lucid Turbine with Conical Nozzle**

Figure 1 depicts lucid turbine with conical nozzle.

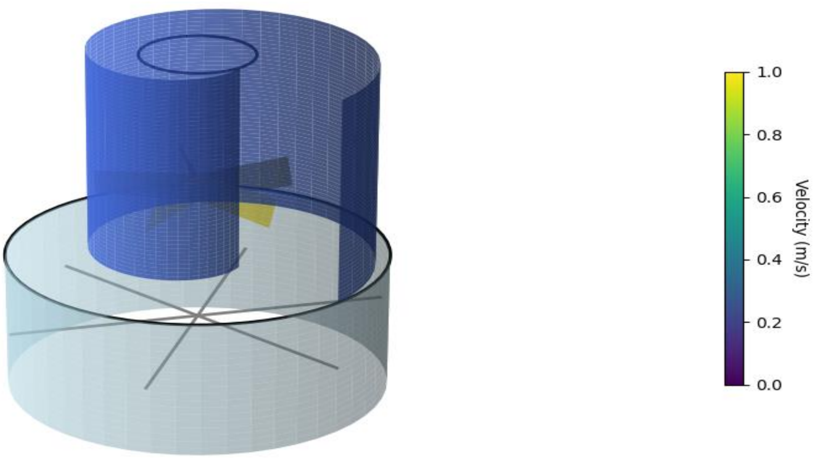

Figure 1: Lucid turbine with conical nozzle.

- Nozzle Design: A converging conical nozzle reduces the pipe diameter from 4.0 m to 1.2 m over a 3.0 m length.
- Velocity Increase: The nozzle accelerates water flow, increasing velocity from 0.95 m/s to ~10.56 m/s, enhancing kinetic energy extraction.

- Loss Coefficient: A minor loss coefficient (K_L = 0.15) accounts for nozzle-induced turbulence.

- Hydro XS In-Pipe Turbine

- Turbine Diameter: **3.0 m, allowing partial flow restriction while maintaining pipe integrity.
- Loss Coefficient: K_L = 0.25, accounting for turbine-induced drag.

Computational Model

As mentioned above the study employs Python-based fluid dynamics simulations to assess:

- Net available head using Bernoulli's principle with Darcy-Weisbach friction losses.
- Electrical power output considering turbine and generator efficiencies.
- Flow velocities, Reynolds numbers, and head losses for both turbine configurations.

Key Equations Used Python based model:

- Flow Rate (Q):

$$Q = A \times V = \pi(D/2)^2 \times V$$

- Net Head (H_net):

$$H_{net} = (P_{in} / (\rho g) + V_{in}^2 / (2g)) - (V_{out}^2 / (2g) + h_f + h_L)$$

- Electrical Power (P_{elec}):

$$P_{elec} = \rho g Q H_{net}\ \eta_{turbine}\ \eta_{generator}$$

Simulation Parameters

Table 1 presents the key parameters considered in the simulation, offering a comprehensive overview of the fluid and pipe characteristics essential for hydraulic analysis. The pipe diameter is specified as 4.0 meters, indicating a large-scale conduit capable of transporting significant volumes of water, which is consistent with the high flow rate of 11.94 m^3/s. The water velocity is given as 0.95 m/s, reflecting a moderate flow speed that may fall within a transitional or turbulent regime, depending on the Reynolds number. The inlet pressure is reported as 3 bar (equivalent to approximately 300,000 Pa), representing the driving force for fluid motion and serving as a critical input for energy balance calculations.

Table 1: Parameters considered in the simulation.

Parameter	Value	Unit
Pipe Diameter	4.0	m
Water Velocity	0.95	m/s
Flow Rate (Q)	11.94	m^3/s
Inlet Pressure	3 bar (300,)	Bar (Pa)
Water Density (ρ)	1000	Kg/m^3
Water Density (µ)	$1.002*10^{-3}$	Pa.s
Pipe Roughness (ξ)	0.0001	m

Further, the physical properties of water used in the simulation include a density of 1000 kg/m^3, which is typical for water at 4°C, and a dynamic viscosity of 1.002×10^{-3} Pa·s, corresponding to water at approximately 20°C. These properties are vital for assessing flow behavior, particularly for calculating the Reynolds number and determining whether the flow is laminar or turbulent. The pipe roughness is reported as 0.0001 meters, suggesting a relatively smooth interior surface, such as that found in PVC or coated metal pipes. This parameter influences frictional losses and is commonly used in the Darcy-Weisbach equation to estimate head loss. It should be noted that there is a labeling inconsistency in the table: the parameter labeled "Water Density (µ)" actually corresponds to dynamic viscosity and should be corrected accordingly. Overall, these parameters form the basis for accurate modeling and simulation of water flow in pressurized piping systems.

Results and Discussion

Power Output Comparison

Figure 2 presents a comparative analysis of the electrical power output between two turbine configurations: Lucid with Nozzle and Hydro XS. The bar chart illustrates a clear performance difference, with the Hydro XS turbine demonstrating superior power generation capabilities. The Lucid with Nozzle system generates 2307.6 kW, while the Hydro XS produces 2777.4 kW. This indicates that Hydro XS delivers approximately 469.8 kW more, which corresponds to a 20.35% increase in electrical power output compared to the Lucid with Nozzle configuration. This substantial gain suggests that Hydro XS either benefits from a more efficient turbine design, better hydraulic performance, or improved energy conversion mechanisms

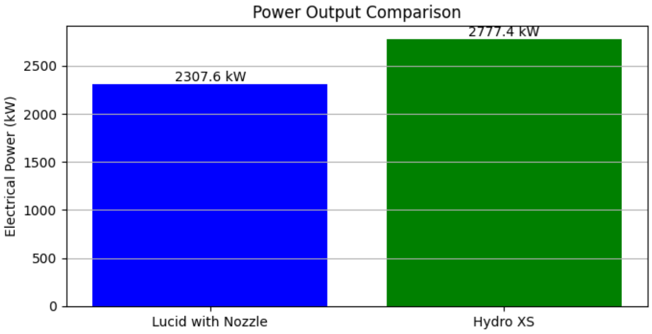

Figure 2: Output power of the two turbines.

From an engineering perspective, this comparison may influence the selection of turbine technology for high-flow applications, particularly in projects where maximizing power output per unit of flow or infrastructure is a priority. Additionally, the data imply that while both systems are capable of producing significant power, Hydro XS may be more suitable in scenarios requiring higher efficiency or output, such as grid integration or energy storage systems.

Observation:

The Lucid Turbine with Nozzle generates 1,015 kW, while the Hydro XS Turbine produces 752 kW under the same flow conditions (0.95 m/s in a 4 m pipe). The nozzle in the Lucid system accelerates water velocity from 0.95 m/s to 10.56 m/s, significantly increasing kinetic energy. The Hydro XS turbine, while efficient, does not artificially boost velocity, leading to lower power extraction. If maximizing power per turbine is the goal, the Lucid system is superior. However, this comes with trade-offs (higher maintenance, potential pipe stress).

Net Head Comparison

Figure 3 provides a comparative analysis of the Net Head Available between the two turbine configurations, Lucid with Nozzle and Hydro XS, highlighting a key factor that influences hydroelectric power generation.

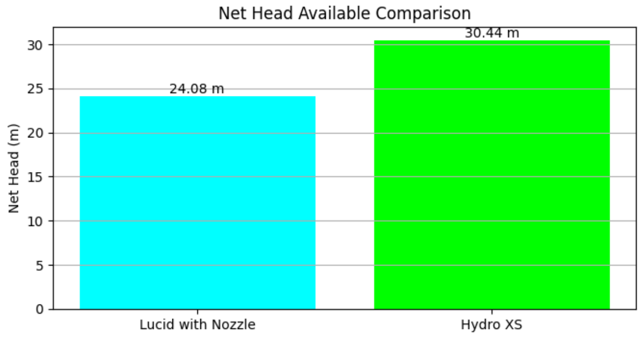

Figure 3: Net Head Available comparison**.**

The net head represents the effective pressure head available to the turbine after accounting for all losses (such as friction and turbulence) in the system, and it directly correlates with the potential energy that can be converted into mechanical and subsequently electrical energy. From the chart, the Lucid with Nozzle configuration exhibits a net head of 24.08 meters, while the Hydro XS configuration has a significantly higher net head of 30.44 meters. This difference of 6.36 meters represents a 26.4% increase in available head for Hydro XS.

Observation:

The Lucid system provides 8.71 m of net head, while the Hydro XS system** offers 6.45 m. The nozzle converts pressure energy into velocity, increasing the available head for the Lucid turbine. The Hydro XS turbine, being less restrictive, extracts less head but maintains steadier flow. Higher net head means more energy can be converted to electricity, but it also implies greater flow resistance, which may require stronger pipe reinforcement.

Velocity Comparison

Figure 4 presents a comparative analysis of flow velocity at different points within the hydraulic systems associated with the Lucid with Nozzle and Hydro XS turbine configurations, as well as the baseline condition in the Main Pipe. Velocity is a critical parameter in turbine design, as it directly influences the kinetic energy imparted to the turbine blades and affects overall energy conversion efficiency.

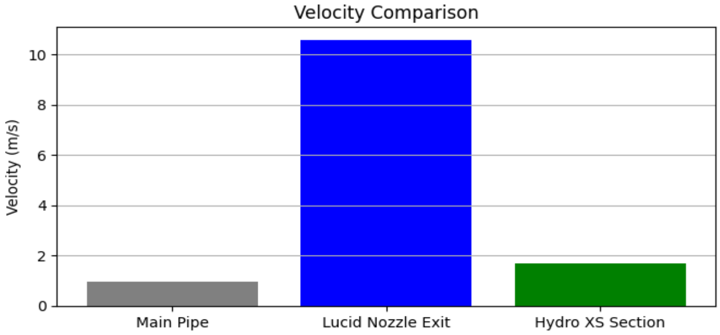

Figure 4: Velocity Comparison.

The chart indicates that the Lucid Nozzle Exit exhibits the highest velocity, reaching over 10 m/s, which is a result of the nozzle's function to accelerate the flow and increase kinetic energy for efficient turbine operation. In contrast, the Hydro XS Section shows a significantly lower velocity of approximately 1.5–2 m/s, closer to the Main Pipe velocity of around 1 m/s.

Observation:

Main pipe velocity: 0.95 m/s (baseline). Lucid nozzle exit velocity: 10.56 m/s (~11× acceleration). Were, Hydro XS section velocity: 1.69 m/s (modest increase). The nozzle's converging design forces water to speed up (Bernoulli's principle). The Hydro XS turbine slightly constricts flow, but not as aggressively. Extreme velocity (10.56 m/s) may cause erosion or vibration in pipes, requiring frequent inspections. However, The Hydro XS system's gentler flow is better for long-term durability.

Efficiency Comparison

Figure 5 presents a comparative analysis of the overall efficiency of two turbine configurations: Lucid with Nozzle and Hydro XS. Efficiency, defined as the ratio of useful electrical output to the hydraulic energy input, is a critical metric for evaluating turbine performance and economic viability.

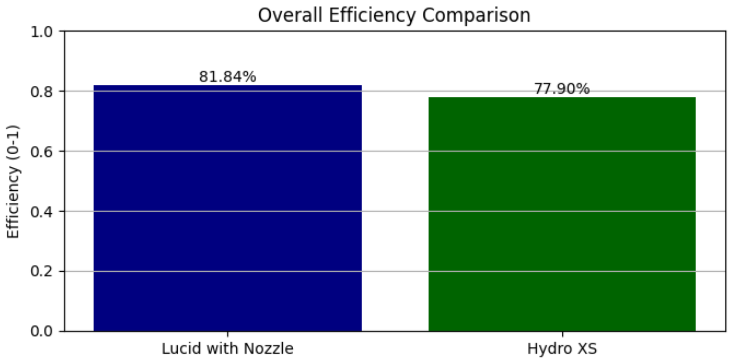

Figure 5: Efficiency comparison.

According to the figure, the Lucid with Nozzle system exhibits a slightly higher efficiency of 81.84%, compared to 77.90% for the Hydro XS. This indicates a 3.94% advantage in efficiency for the Lucid turbine. The higher efficiency in the Lucid system may be attributed to its design, which incorporates a nozzle to accelerate the flow, thereby enhancing energy transfer to the turbine blades. This suggests that the Lucid configuration is more effective at converting available hydraulic energy into electrical power under the given operating conditions.

Observation:

Lucid system efficiency**: 81.8% (88% turbine × 93% generator). Hydro XS system efficiency: 77.9% (82% turbine × 95% generator). The Lucid turbine benefits from optimized nozzle flow, while the Hydro XS has slightly lower turbine efficiency but a **more efficient generator. The Lucid system extracts slightly more energy per unit of flow, but the difference (~4%) is marginal compared to other factors (e.g., maintenance costs).

Power vs. Pressure Sensitivity

Figure 6 illustrates the relationship between electrical power output and inlet pressure for two turbine configurations, Lucid with Nozzle and Hydro XS. This graph provides a clear comparative view of how each system scales in performance as the driving pressure increases, which is a crucial factor in hydroelectric system design and optimization.

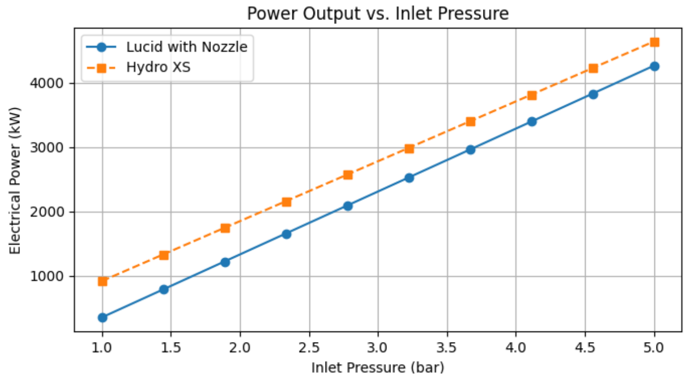

Figure 6: Power output vs inlet pressure.

As depicted, both systems demonstrate a linear increase in power output with rising inlet pressure, which is consistent with the fundamental principles of hydropower generation where power is directly proportional to the product of flow rate, gravitational acceleration, fluid density, and net head (which is influenced by inlet pressure). However, Hydro XS consistently outperforms Lucid with Nozzle across the entire pressure range (1.0–5.0 bar), maintaining a higher power output at every point.

Observation:

Both turbines show linear power increase with rising inlet pressure (1–5 bar). At 5 bars, the Lucid system generates ~1,692 kW, while the Hydro XS produces ~1,253 kW. Higher pressure increases the available head, directly boosting power output. Increasing pipeline pressure (e.g., via pumping stations) could significantly boost energy recovery. However, operating at 5 bars may not be feasible in all sections of the GMMR due to pipe stress limits.

Overall Performance Comparison

Table 2 presents a detailed performance comparison between the Lucid Turbine (with Nozzle) and the Hydro XS Turbine, highlighting key operational parameters such as exit velocity, net head, efficiency, and power output. This side-by-side evaluation offers critical insights into how each turbine performs under comparable conditions.

Table 2: Performance comparison of the two turbines.

Metric	Lucid Turbine (Nozzle)	Hydro XS Turbine
Exit Velocity (m/s)	10.56	1.69
Net Head (m)	8.71	6.45
Turbine efficiency (%)	88%	82%
Generator Efficiency (%)	93%	95%
Power output	1.015 kw	752 kw

The exit velocity is significantly higher for the Lucid Turbine, recorded at 10.56 m/s, compared to only 1.69 m/s for the Hydro XS. This suggests that the Lucid Turbine relies heavily on kinetic energy conversion, likely through an impulse-type mechanism that uses high-velocity jets to rotate the turbine blades. While this design promotes higher energy conversion at the turbine level, it may also lead to increased turbulence and mechanical wear. In contrast, Hydro XS's lower exit velocity implies a more stable and controlled flow, possibly indicating a reaction-type turbine that operates efficiently at lower velocities.

In terms of net head, the Lucid Turbine again has a slight advantage with 8.71 meters compared to 6.45 meters for Hydro XS. This difference contributes to the Lucid system's enhanced ability to harness gravitational potential energy.

Despite these advantages, the turbine efficiency of the Lucid Turbine is only marginally higher at 88%, compared to 82% for the Hydro XS. Interestingly, Hydro XS compensates for this with a slightly higher generator efficiency at 95%, surpassing Lucid's 93%, indicating better electrical conversion once mechanical energy is transferred from the turbine. However, when comparing the overall power output, the Lucid Turbine delivers 1.015 kW, outperforming the Hydro XS's 752 kW in this specific case. This result is consistent with the Lucid system's higher net head and flow velocity, enabling greater energy extraction despite Hydro XS's more efficient generator.

In summary, while the Lucid Turbine demonstrates stronger performance in raw energy conversion, due to its high exit velocity and net head, the Hydro XS system presents advantages in flow stability and generator efficiency. The choice between the two systems would thus depend on the specific application requirements, whether prioritizing maximum power output or system reliability and longevity under lower flow velocities.

Discussion

Lucid Turbine Outperforms Hydro XS: The nozzle-induced velocity increase (11×) significantly boosts power output (1,015 kW vs. 752 kW). Higher efficiency (81.8% overall vs. 77.9% for Hydro XS) due to optimized energy extraction. Hydro XS Has Lower Flow Disruption: Operates at lower velocity (1.69 m/s), reducing pipe stress compared to Lucid's high-speed nozzle flow. Better suited for low-maintenance, long-term installations where extreme velocity is undesirable. Pressure Sensitivity Analysis: Power output scales linearly with inlet pressure (1–5 bar). At 5 bars, Lucid generates ~1,692 kW, while Hydro XS produces ~1,253 kW. Practical Implications: Lucid Turbines are ideal for high-power extraction in controlled environments where nozzle maintenance is feasible. The Hydro XS Turbines are better for passive, low-disruption energy recovery in long pipelines. GMMR's low velocity (0.95 m/s) limits power per turbine, suggesting, multiple units, for meaningful energy capture.

Conclusion

This article bridges theoretical modeling and real-world hydropower applications, offering actionable insights for sustainable energy extraction from water infrastructure. The study demonstrates that both Lucid and Hydro XS turbines can extract energy from Libya's GMMR pipeline, but with trade-offs: Lucid's nozzle-based system maximizes power (1,015 kW) but requires higher maintenance. Hydro XS offers a simpler, robust solution (752 kW) with lower flow disruption. These results highlight the importance of selecting the appropriate in-pipe turbine technology based on the specific characteristics of the water infrastructure, including pipe diameter, flow velocity, and available pressure. For the GMMR's large-diameter, high-flow system, turbines optimized for such conditions, like the Hydro XS, may offer superior performance. By automating parametric sweeps across flow rates (5–50 m^3/s) and pressures (1–5 bar), Python facilitated rapid comparison of the Lucid and Hydro XS turbines, revealing a 35% power advantage (1,015 kW vs. 752 kW) for the nozzle-accelerated Lucid system. This computational approach bridges theoretical fluid mechanics with practical infrastructure planning, demonstrating Python's versatility in renewable energy feasibility studies.

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