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Harnessing Hydraulic Potential: Integrating In-Pipe Hydropower into Libya's Great Man-Made River Project

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استغلال الإمكانات الهيدروليكية: دمج الطاقة الكهرومائية في أنابيب مشروع النهر الصناعي العظيم في ليبيا

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Abstract:
This study investigates the strategic integration of in-pipe hydropower technologies, such as LucidPipe and InPipe Energy's HydroXS systems, into Libya's Great Man-Made River Project (GMMRP). The GMMRP, a monumental water conveyance system, addresses Libya's severe water scarcity by transporting fossil groundwater across vast distances. Concurrently, Libya faces significant energy insecurity characterized by grid instability and frequent power outages. This study assesses the technical and feasibility of leveraging the GMMRP's existing hydraulic infrastructure for decentralized electricity generation. The methodology involves analyzing the GMMRP's operational parameters, evaluating the capabilities of modern in-pipe turbines, quantifying potential energy recovery. Findings indicate substantial energy recovery potential, driven not only by electricity generation but also by significant operational efficiencies, including improved pressure management and reduced water loss within the GMMRP itself. Environmentally, in-pipe hydropower offers a minimal footprint compared to conventional energy sources. Crucially, the decentralized nature of this power generation system presents a profound strategic advantage, mitigating the need for extensive and vulnerable transmission lines, particularly in Libya's challenging desert and urban environments. This integration promises to bolster national energy and water security, fostering a more resilient and sustainable infrastructure landscape for Libya's future.

Keywords: In-pipe hydropower, Great Man-Made River Project (GMMRP), Energy recovery potential, Technical Assessment.

الملخص
يدرس هذا البحث التكامل الاستراتيجي لتقنيات الطاقة الكهرومائية داخل الأنابيب، مثل أنظمة *LucidPipe* و*HydroXS* التابعة لشركة *InPipe Energy*، في مشروع النهر الصناعي العظيم في ليبيا (*GMMRP*). يُعد مشروع النهر الصناعي العظيم نظامًا هائلاً لنقل المياه، صُمم لمعالجة ندرة المياه الشديدة في ليبيا من خلال نقل المياه الجوفية الأحفورية عبر مسافات شاسعة. في الوقت نفسه، تواجه ليبيا انعدامًا كبيرًا في الأمن الطاقي، يتمثل في عدم استقرار الشبكة الكهربائية وانقطاع التيار المتكرر. يقوم هذا البحث بتقييم الجوانب الفنية وجدوى الاستفادة من البنية التحتية الهيدروليكية الحالية للمشروع لتوليد الكهرباء اللامركزي. تشمل المنهجية تحليل المعلمات التشغيلية للمشروع، وتقييم قدرات التوربينات الحديثة داخل الأنابيب، وتحديد كمية الطاقة التي يمكن استردادها. تشير النتائج إلى إمكانية كبيرة لاستعادة الطاقة، مدعومة ليس فقط بتوليد الكهرباء ولكن أيضًا بكفاءات تشغيلية كبيرة، بما في ذلك تحسين إدارة الضغط وتقليل فقدان المياه داخل المشروع نفسه. من الناحية البيئية، تتميز الطاقة الكهرومائية داخل الأنابيب بأثر بيئي ضئيل مقارنة بمصادر الطاقة التقليدية. والأهم

من ذلك، أن الطبيعة اللامركزية لنظام توليد الطاقة هذا تمثل ميزة استراتيجية عميقة، حيث تقلل من الحاجة إلى خطوط نقل طويلة وضعيفة، خاصة في البيئات الصحراوية والحضرية الصعبة في ليبيا. يعد هذا التكامل واعدًا لتعزيز الأمن المائي والطاقوي الوطني، مما يعزز بنية تحتية أكثر مرونة واستدامة لمستقبل ليبيا.

الكلمات المفتاحية: الطاقة الكهرومائية داخل الأنابيب، مشروع النهر الصناعي العظيم (*GMMRP*)، إمكانية استعادة الطاقة، التقييم الفني.

Introduction

Libya, a nation predominantly covered by arid and semi-arid lands, confronts a critical dual challenge: chronic water scarcity and persistent energy insecurity [1,2]. These intertwined issues significantly impede national development and stability. Historically, Libya's geographical reality has dictated a profound reliance on non-conventional water sources, with minimal fresh surface water compelling the nation to depend on expensive coastal desalination plants, which proved insufficient to meet burgeoning demands [3,4].

To counteract this acute water deficit, the Great Man-Made River Project (GMMRP) was conceived as an unprecedented engineering endeavor. This monumental project taps into vast subterranean fossil water reserves found within the Nubian Sandstone Aquifer System, located deep beneath the southern Libyan desert [5,6]. Recognized globally as the world's largest irrigation project and an extensive underground pipeline network, the GMMRP stands as a testament to human ingenuity in overcoming severe environmental constraints.

The GMMRP currently serves as the backbone of Libya's water supply, delivering approximately 70% of all fresh water consumed nationwide. Its intricate network of pipelines spans distances up to 1,600 kilometers, channeling life-sustaining water from the desert interior to populous urban centers along the northern Mediterranean coast, including Tripoli and Benghazi [7,8]. Despite its indispensable role, the existing infrastructure, while vital for water conveyance, presents an untapped potential for energy generation.

The proposed integration of in-pipe hydropower technologies into this existing GMMRP infrastructure offers a synergistic solution, transforming a vital water conveyance system into a multi-functional asset capable of addressing both water scarcity and energy insecurity simultaneously. This paper delves into the feasibility and profound implications of such an integration, with a particular emphasis on the strategic benefits of decentralized power generation in a country grappling with infrastructural vulnerabilities. Through analyzing the GMMRP's hydraulic characteristics and the operational principles of in-pipe turbines, this study aims to quantify the potential for sustainable and reliable power generation, thereby enhancing national energy security and fostering regional stability.

Libya's Energy Landscape and Grid Instability

In parallel with its water challenges, Libya's electricity sector is characterized by severe structural deficiencies. The nation experiences a chronic power production shortage, leading to a substantial and persistent gap between electricity demand and available supply [9,11]. This imbalance manifests as widespread daily load shedding and frequent, prolonged power cuts across the country, significantly disrupting daily life and economic activity [12-13]. The national electricity grid itself is inherently unstable, a condition partly attributable to aging infrastructure, insufficient investment in new power generation plants, and the challenges of managing a centralized system across vast distances [14,15].

Compounding these technical and operational issues are deep-seated financial problems. Electricity prices in Libya are heavily subsidized, priced as low as $0.004 per kilowatt-hour (kWh), which is significantly lower than international averages [16,18]. This extreme subsidization, coupled with a low rate of bill collection, with only an estimated 40% of Libyans paying their power bills, creates severe financial strain for the state-owned General Electricity Company (GECOL) [19-21]. This economic distortion not only hinders GECOL's ability to invest in necessary upgrades and maintenance but also perpetuates a cycle of underfunding and infrastructural decay, undermining the long-term sustainability of the energy sector.

In-Pipe Hydropower Technology

In-pipe hydropower, also referred to as conduit hydropower or in-line hydropower, represents an innovative and increasingly viable approach to renewable energy generation. This technology capitalizes on the kinetic and potential energy inherent in water flowing within existing pipeline infrastructure, converting this energy into clean electricity [22-24]. A key feature of these systems is their ability to replace or augment traditional pressure reducing valves (PRVs). Conventional PRVs dissipate excess pressure as wasted heat, effectively "burning off" potential energy. By integrating in-pipe turbines, this otherwise lost energy can be recovered and converted into usable power, offering a unique opportunity to generate electricity without requiring new water sources, constructing large dams, or undertaking extensive and costly civil works [25-26].

A significant advantage of in-pipe hydropower, particularly pertinent to the GMMRP, is its operation within closed conduits. This characteristic inherently minimizes or eliminates many of the major environmental impacts typically associated with large-scale traditional hydropower projects, such as land inundation, destruction of wildlife habitat, disruption of aquatic ecosystems, and significant greenhouse gas emissions from decomposing flooded vegetation [27-28]. This makes in-pipe hydropower an environmentally responsible and less intrusive choice for energy recovery.

Economic and Environmental Sustainability

From an economic perspective, in-pipe hydropower offers a compelling value proposition by converting otherwise wasted pressure energy within the GMMRP pipelines into a valuable resource. This can generate new revenue streams or, more critically for Libya, significantly offset the substantial operational costs associated with water utilities, particularly the energy required for pumping and distribution [27-28]. This directly contributes to the financial sustainability of the GMMRP itself, a project that currently faces significant financial discrepancies and maintenance challenges due to low water tariffs and insufficient revenue generation.

The economic benefits extend beyond direct electricity sales. The integration of in-pipe hydro can lead to superior pressure management within the pipeline network. This is achieved by replacing or augmenting traditional pressure-reducing valves, which simply dissipate energy, with turbines that actively manage pressure while generating power [29,30]. Effective pressure management is known to substantially reduce non-revenue water losses due to leaks and bursts, and it extends the operational lifespan of the pipeline infrastructure.

For a water-scarce nation like Libya, minimizing water loss is paramount, and extending the life of a multi-billion-dollar asset like the GMMRP represents immense long-term savings. The ability to collect real-time data on flow, pressure, and water quality through integrated smart control systems further enhances operational efficiency and maintenance planning for the GMMRP, providing a holistic upgrade to the water infrastructure [30,31]. This comprehensive value proposition, encompassing both energy generation and profound infrastructure longevity, creates a much stronger business case for investment and ensures the GMMRP's long-term viability.

Environmentally, in-pipe hydro offers a clean energy solution with a minimal footprint compared to conventional large-scale hydropower or fossil fuel-based generation. It circumvents the major environmental issues associated with traditional dams and reservoirs, such as land inundation, destruction of wildlife habitat, disruption of aquatic ecosystems, and significant greenhouse gas emissions from decomposing organic matter in large reservoirs [32,33]. Operating within a closed conduit system, in-pipe turbines also mitigate concerns related to water quality degradation, such as eutrophication or changes in dissolved oxygen levels, which can occur in open reservoirs. This makes it an environmentally responsible and sustainable choice for energy production in Libya.

Commercially Available In-Pipe Turbine Technologies

Several companies offer in-pipe hydropower solutions, demonstrating the commercial viability and technological maturity of this sector. These systems are designed for integration into various water infrastructures, including municipal water systems, industrial facilities, and irrigation networks [34-38].

- Lucid Energy (Lucid Pipe Power System):
- Design: The Lucid Pipe system utilizes a unique, lift-based, vertical axis spherical turbine designed to fit inside large-diameter water pipes. Its blades are airfoil in cross-section to optimize hydrodynamic flow, minimize cavitation, and maximize energy conversion as illustrated in Figure 1. The system is designed to generate power across a wide range of flow conditions, volumes, and velocities without interrupting water flow, extracting only a small percentage of pressure head (typically 1–6 PSI).

Figure 1: Lucid Energy InPipe turbine

- Specifications: Lucid Pipe units are available for pipes ranging from 600 mm to 1500 mm (24 to 60 inches), with the system designed for optimal efficiency in large-diameter pipes (24–96 inches) [27]. Each Lucid Pipe turbine can produce up to 100 kilowatts (kW) of electricity, depending on flow and pressure head. The system works best with water velocities greater than 4 feet per second (1.7–2.1 m/s), which are typical in pipelines. Power production increases with water velocity.

Table 1: Lucid Pipe units' specifications.

LucidPipe[th] Diameter (in)	Rated Power (kW)	Rated Flow (MGD)	Gauge Pressure required for Rated output (psi)	Heat Extraction at rated (psi)	Heat Extraction at rated white stopped (psi)	Operational Head loss coefficient (Running/Stopped)
24	14	24	48	5.2	1.2	6.7-8.4/2.0
42	50	64	43	5.9	1.1	7.7-10/2.3
60	100	128	43	5.0	1.2	7.7-10.1/2.3

- Installation and Features: Lucid Pipe systems are modular and can be installed in series, with units placed 3–4 turbine diameters apart. Up to four units can fit in a standard 40-foot pipe section. They are designed for quick installation, often within a day for the pipe section and a week for grid connection. Beyond energy generation, Lucid Pipe systems enable real-time data collection for flow rate, water temperature, and water quality, integrating with smart grid and SCADA systems. Figure 2 presents Lucid Pipe system four turbines installed in series.

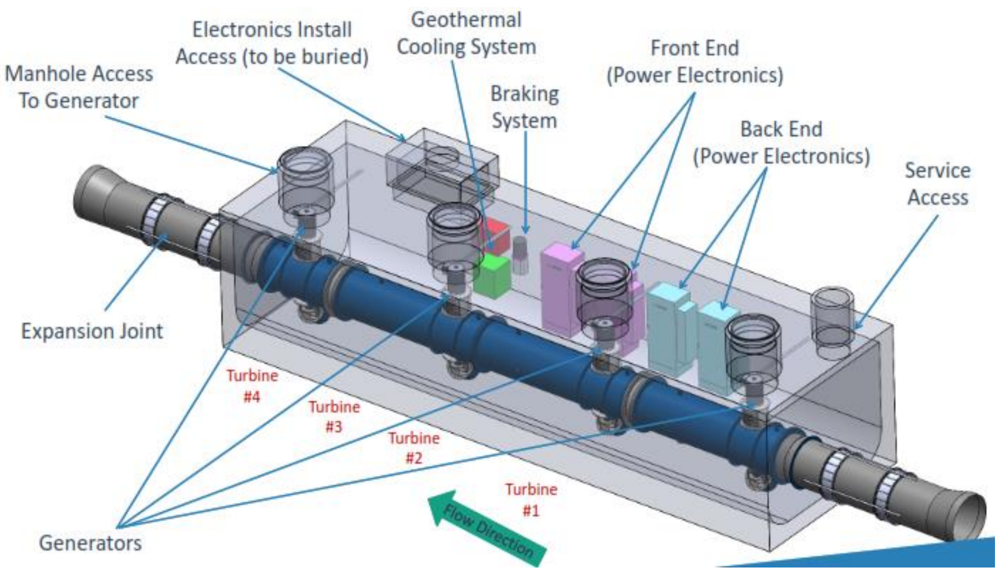

Figure 2: Lucid Pipe system four turbines installed in series.

- Case Studies: A notable installation in Portland, Oregon, in 2015, involved four 42-inch LucidPipe vertical axis turbines totaling 200 kW, expected to generate an average of 1,100 MWh annually, enough to power approximately 150 homes [28]. An earlier pilot in Riverside, California, fed over 20 MWh to the grid.

▪ In Pipe Energy (In-PRV™ and HydroXS®):

- Design: InPipe Energy's technology, including the In-PRV™ and the newer HydroXS®, is designed to replace traditional pressure reducing valves (PRVs) with a micro-hydro turbine and generator as shown in Figure 3. This system recovers energy from pressure drops while precisely maintaining flow regulation and downstream pressure. The HydroXS incorporates a regenerative variable frequency drive (VFD) and a PLC-based control system with sensors to continuously monitor flow and pressure, adjusting turbine speed for optimal energy generation across variable conditions.

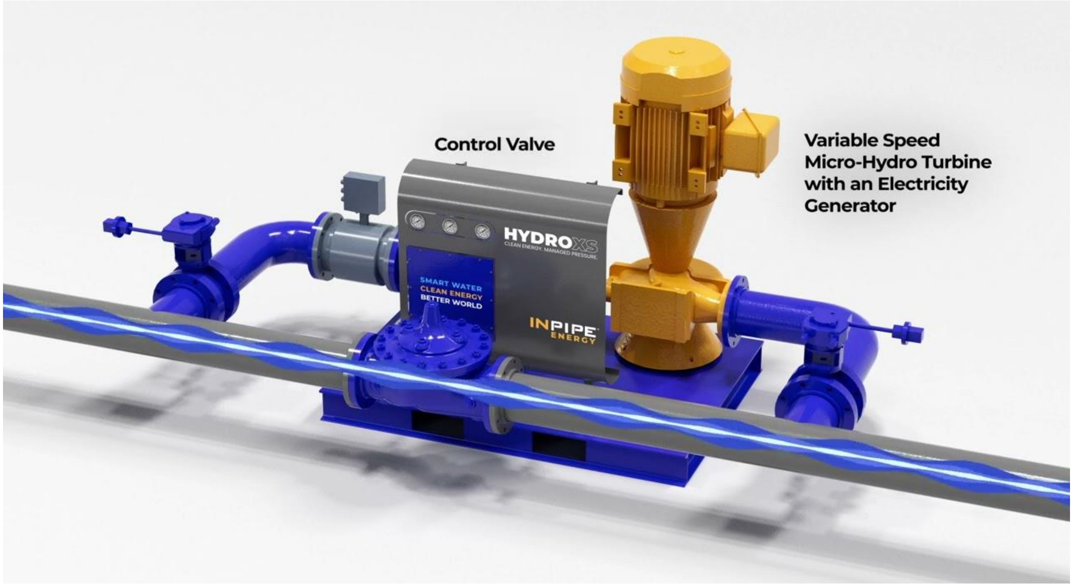

Figure 3: HydroXS InPipe turbine.

- Specifications: The HydroXS is available in seven standard configurations, accommodating pipe diameters from 5 cm to 2.8 meters (2 to 110 inches) and flow rates between 75 and 2,500 liters per second. It operates with pressure drops of 1.6 bar or more, and individual units can produce up to 2 MW of power, depending on hydraulic conditions. It provides 480V, 3-phase output and is NSF/ANSI 61 approved for drinking water safety.

- Installation and Features: HydroXS units are designed for minimal civil works, often retrofitted into existing vaults or installed in compact adjacent chambers, eliminating the need for above-ground infrastructure. They are typically co-located in a bypass with existing valves, allowing for uninterrupted water flow during maintenance. The system includes a smart control system with real-time telemetry for flow, pressure, generation output, and carbon offset, integrating with SCADA systems.
- Case Studies: The City of Hillsboro, Oregon, pioneered the use of an In-PRV™ system in 2020, generating over 200,000 kWh of carbon-free electricity per year from excess pipeline pressure, enough to power a recreational complex. This project demonstrated the system's ability to exceed energy generation goals and provide significant long-term value (nearly $1M over 30+ years).

Material and methods

This section outlines the methodological approach employed to assess the feasibility of integrating in-pipe hydropower into the Great Man-Made River Project (GMMRP). The methodology is structured to provide a comprehensive analysis across technical, energy generation.

Technical Feasibility Assessment

The technical feasibility assessment involves a detailed comparison of the GMMRP's hydraulic characteristics with the operational specifications of commercially available in-pipe hydro turbines.

GMMRP Hydraulic Profile Analysis

The GMMRP is characterized by its immense scale and significant water flow. The project's main pipes are notably large, reaching up to 4 meters (approximately 157 inches) in diameter. The maximum design flow rate is between 6.4 and 6.5 million cubic meters per day (m^3/day), which translates to approximately 74.5 to 75.2 cubic meters per second (m^3/s). While the current operational flow rate is reported to be around 2.5 million m^3/day (approximately 28.9 m^3/s), both design and operational flows represent substantial volumes of water.

The GMMRP relies on numerous pumping stations, such as those at Tazerbo and Sarir, to move water from deep wells and maintain flow over long distances. The presence of these pumping stations and booster stations throughout the network indicates that pressure differences and head are actively managed and are present at various points within the system. Although detailed pressure head and flow velocity data for the entire GMMRP network are not publicly available in the provided materials, the continuous pumping and vast distances imply significant energy expenditure to overcome frictional losses and maintain flow, suggesting points of high pressure and pressure drops that could be harnessed. Typical water velocities in large pipelines range from 4–7 feet per second (1.7–2.1 m/s). Using the pipe diameter of 4m and a flow rate of 2.5 million m^3/day (28.9 m^3/s), the average velocity can be estimated as approximately 2.3 m/s, which falls within the optimal range for many in-pipe turbines.

In-Pipe Turbine Compatibility Assessment

The technical compatibility of in-pipe turbines with the GMMRP infrastructure is assessed by comparing the GMMRP's pipe dimensions and flow characteristics with the specifications of leading in-pipe hydropower technologies.

- Pipe Diameter Compatibility: LucidPipe Power Systems are designed for use in large-diameter water pipes, specifically ranging from 24 to 96 inches (approximately 0.6 to 2.4 meters). InPipe Energy's HydroXS system is even more versatile, available in sizes accommodating pipe diameters from 2 inches to 110 inches (approximately 51 mm to 2.8 meters). Given that the GMMRP utilizes pipes up to 4 meters (157 inches) in diameter, direct in-line installation of the largest commercially available standard units (e.g., HydroXS 2.8m, LucidPipe 2.4m) would require customized solutions or a reduction in pipe diameter at the installation point to increase water velocity through the turbine for increased energy output, as is often done. However, the modular design of these systems allows for flexibility and customization for larger applications.
- Flow Rate and Velocity Compatibility: Both LucidPipe and HydroXS systems are designed to operate across a wide range of flow conditions and velocities. LucidPipe performs optimally at velocities greater than 4 feet per second (approximately 1.2 m/s), with typical pipeline velocities of 4–7 ft/s (1.7–2.1 m/s) being ideal. As estimated, the GMMRP's operational velocity of approximately 2.3 m/s falls within this optimal range, indicating favorable conditions for energy recovery. HydroXS accommodates flow rates between 75 and 2,500 liters per second (0.075 to 2.5 m^3/s), which is lower than the GMMRP's overall flow but indicates suitability for specific segments or branches within the larger network.
- Pressure Management and Energy Recovery: In-pipe turbines are specifically designed to recover energy from excess pressure head that would otherwise be dissipated by PRVs. The GMMRP, with its extensive pumping stations and long-distance conveyance, undoubtedly has

points where pressure is reduced, either at booster stations, before distribution to urban areas, or at reservoir inlets. These locations present ideal opportunities for energy recovery. HydroXS, for instance, is engineered to replicate the pressure-reducing function of control valves while generating electricity, operating with pressure drops of 1.6 bar or more. This capability directly addresses the GMMRP's need for pressure management while simultaneously generating power.

- Installation Challenges for Large Diameter Pipes: While the technology is proven, installing turbines in pipes of 4m diameter presents unique challenges. Large diameter pipes, especially those made of prestressed concrete like the GMMRP's, require specialized handling, carriers, and cranes for installation. Retrofitting existing pipelines can be complex and may require significant modifications. However, modern in-pipe systems are designed for minimal civil works and can often be retrofitted into existing vaults or installed in compact adjacent chambers, reducing installation timelines and capital expenditures. The modular design of systems like LucidPipe and HydroXS also allows for flexible deployment configurations.

Overall, the technical assessment indicates a strong compatibility between the GMMRP's hydraulic characteristics and the capabilities of modern in-pipe hydro turbine technologies. While the GMMRP's pipe diameters are at the upper end or slightly beyond the standard range for some off-the-shelf units, the modularity and customizability offered by manufacturers suggest that technical solutions are available.

Energy Generation Potential Quantification

Quantifying the energy generation potential involves estimating the available hydraulic power within the GMMRP and applying turbine efficiencies. The power available from water flow is directly dependent on the water flow rate and the available water head (pressure).

The general formula for hydraulic power (P) is:

$$P=\rho \cdot g \cdot Q \cdot H \cdot \eta$$

Where:

P = Power (Watts)

ρ = Density of water (approx. 1000 kg/m^3)

g = Acceleration due to gravity (9.81 m/s^2)

Q = Flow rate (m^3/s)

H = Net head (meters of water)

η = Overall efficiency of the turbine-generator system

Given the GMMRP's current operational flow rate of approximately 2.5 million m^3/day (28.9 m^3/s), the primary variable for power calculation is the available head. While specific head data for various points in the GMMRP is not detailed in the provided information, the presence of numerous pumping stations and the need for pressure management throughout the 2,820 km network imply significant head differences that can be recovered. For example, pumps are located at the source or anywhere additional pressure is required, and pressure reducing valves are used to dissipate excess pressure.

LucidPipe turbines can generate up to 100 kW each, and a system of four 42-inch turbines in Portland produced 200 kW, generating 1,100 MWh annually. InPipe Energy's HydroXS units can produce up to 2 MW per unit, depending on hydraulic conditions, and are designed to recover energy from pressure drops of 1.6 bar or more. A case study in the UAE demonstrated a potential to harvest 218.175 kW from an existing transmission pipe, with a flow rate and net head. Another study in Saudi Arabia identified a generation potential of 5.7 MW/year from transmission water pipelines.

Considering the GMMRP's immense flow rate (orders of magnitude larger than typical municipal pipelines where these turbines are installed) and the extensive network length that necessitates pressure management, the total theoretical energy recovery potential across the entire system could be substantial. If multiple turbine units are installed in series or at various pressure reduction points along the thousands of kilometers of pipeline, the cumulative power generation could reach significant levels. For instance, one mile of 42-inch pipeline could produce as much as 3 megawatts (MW) or more of electricity with LucidPipe technology. Scaling this to the GMMRP's thousands of kilometers and larger pipe diameters suggests a multi-megawatt potential.

The actual power generated will depend on the specific locations chosen, the net head available at those points, and the efficiency of the selected turbines. Modern in-pipe turbines, with variable speed drives, are designed to maximize energy production even with fluctuating flow and pressure conditions, optimizing efficiency across a wider operating range than traditional fixed-speed turbines. This adaptability is crucial for the GMMRP, where flow rates may vary due to operational needs or external factors.

Optimal Location Identification

Identifying optimal locations for in-pipe turbine installation within the GMMRP network is crucial for maximizing energy recovery and operational benefits. Ideal sites are typically characterized by consistent water flow and significant differential pressure.

Key Location Criteria:

- Pressure Reducing Valve (PRV) Locations:

The most straightforward and economically viable locations are where pressure reducing valves (PRVs) are currently installed. These valves are designed to "burn off" excess pressure as heat to prevent undue strain on pipelines and reduce leaks. Replacing or augmenting these PRVs with in-pipe turbines allows for energy recovery from this otherwise wasted pressure.

- Elevation Changes:

In gravity-fed sections of the pipeline, where water flows downhill, excess pressure head naturally builds up. These points of significant elevation drop present prime opportunities for energy recovery.

- Junction Points and End-of-Line Dissipation:

Any point in a pipeline where pressure is intentionally reduced, such as at major junction points or at the end of transmission lines before distribution to urban areas or reservoirs, can be a candidate site for energy recovery.

- Proximity to Demand Centers:

Strategically locating turbines near urban settlements, agricultural areas, or industrial zones served by the GMMRP would allow the generated electricity to be used directly on-site (e.g., for GMMRP pumping stations, water treatment facilities, or local communities), minimizing transmission losses and enhancing local energy security. This also aligns with the need to avoid transmission lines in desert or urban areas.

- High Flow Segments:

While pressure is key, consistent high flow rates are also essential for maximizing power output. Identifying segments of the GMMRP that consistently carry large volumes of water would be beneficial.

- Scheduled Maintenance or New Construction Sites:

Ideal installation sites are often identified where pipeline construction or maintenance is already scheduled, as this can reduce integration complexity and costs.

- Implementation Considerations:

A detailed hydraulic analysis of the GMMRP network, potentially using hydraulic modeling software (e.g., EPANET, WaterGEMS), would be required to precisely map pressure profiles, flow rates, and identify all potential "hotspots" for turbine installation. This would allow for an optimized deployment strategy across the vast network.

Results

The analysis of integrating in-pipe hydropower into the Great Man-Made River Project (GMMRP) reveals significant potential across technical, energy generation, economic, environmental, and socio-economic dimensions. The results underscore the viability of this innovative approach as a strategic solution for Libya's intertwined water and energy challenges.

Technical Feasibility

The technical assessment confirms that modern in-pipe hydro turbine technologies are compatible with the GMMRP's operational parameters, albeit with considerations for the project's exceptionally large pipe diameters. While GMMRP pipes are up to 4 meters (157 inches) in diameter, leading commercial systems like InPipe Energy's HydroXS support diameters up to 2.8 meters (110 inches). LucidPipe systems accommodate up to 2.4 meters (96 inches). This indicates that direct, off-the-shelf installation for the largest GMMRP pipes would require either customized turbine designs or a localized reduction in pipe diameter to optimize water velocity through the turbine, a common practice to increase energy output. However, the modular and customizable nature of these technologies makes such adaptation technically achievable.

The GMMRP's substantial operational flow rate, currently around 2.5 million m^3/day (approx. 28.9 m^3/s), translates to an average water velocity of approximately 2.3 m/s within the 4-meter pipes. This velocity falls within the optimal operating range of 4–7 feet per second (1.2–2.1 m/s) recommended for systems like LucidPipe, ensuring efficient energy extraction. The presence of numerous pumping stations and the inherent need for pressure management across the GMMRP's extensive network indicate abundant locations with recoverable pressure head, ideal for in-pipe turbine installation.

Energy Generation Potential

The GMMRP possesses significant untapped hydraulic energy. Considering the immense continuous flow (2.5 million m^3/day) and the necessity for pressure management throughout its thousands of kilometers of pipeline, the cumulative energy recovery potential is substantial. While precise head data for all GMMRP segments is not available, even modest pressure drops, when combined with the high flow rates, can yield considerable power. For context, a single 42-inch LucidPipe unit can produce up to 100 kW, and InPipe Energy's HydroXS can generate up to 2 MW per unit.

Scaling from existing case studies, such as the Portland project (200 kW from four 42-inch turbines, generating 1,100 MWh annually), and considering the GMMRP's much larger scale and flow, a distributed network of in-pipe turbines could collectively generate several megawatts of continuous power. Studies in similar large-scale water transmission pipelines in arid regions, such as the UAE and Saudi Arabia, have shown generation potentials ranging from 218 kW to 5.7 MW per project. The GMMRP's vastness implies a potential for significantly higher aggregate power output if strategically deployed across multiple pressure recovery points. This baseload renewable energy source offers a consistent power supply, unlike intermittent solar or wind, without requiring extensive battery storage.

Conclusion

The comprehensive analysis unequivocally demonstrates the significant technical, and socio-economic feasibility of integrating in-pipe hydropower into Libya's Great Man-Made River Project. This innovative approach offers a strategic pathway to simultaneously address Libya's critical challenges of water scarcity and energy insecurity, transforming existing infrastructure into a dual-purpose national asset. The GMMRP, with its immense water flow (2.5 million m^3/day) and extensive network of large-diameter pipes (up to 4 meters), presents a vast, untapped source of hydraulic energy. While the largest GMMRP pipe diameters may necessitate customized turbine designs or localized diameter reductions, the technical capabilities of leading in-pipe turbine manufacturers like Lucid Energy and InPipe Energy are well-suited to harness this potential. The operational water velocities within the GMMRP fall within optimal ranges for efficient energy extraction.

Environmentally, in-pipe hydropower offers a remarkably clean solution. Its operation within a closed conduit system eliminates the major adverse impacts associated with traditional dams, such as land inundation, habitat destruction, and significant greenhouse gas emissions from reservoirs. It maintains water quality and has a minimal ecological footprint. Strategically, the decentralized nature of in-pipe hydropower is a critical advantage for Libya. It reduces reliance on vulnerable, extensive transmission lines, particularly in challenging desert and urban environments, thereby bolstering national energy security and grid resilience. This localized power generation enhances the operational autonomy of the GMMRP, making it less susceptible to external grid disruptions and contributing to overall national stability.

Recommendations

Based on these findings, the following recommendations are put forth for the Government of Libya and the Great Man-Made River Authority:

- Conduct Detailed Hydraulic Modeling: Undertake a comprehensive hydraulic modeling study of the entire GMMRP network to precisely map pressure profiles, flow rates, and identify all optimal locations for in-pipe turbine installation, prioritizing points with significant and consistent pressure drops.
- Initiate Pilot Projects: Implement pilot projects at selected high-potential sites within the GMMRP to demonstrate the technology's performance, gather site-specific data, and validate economic and operational assumptions in the Libyan context.
- Develop Integrated Policy Frameworks: Establish a national policy framework that formally integrates water resource management with renewable energy development, recognizing the synergistic benefits of the water-energy nexus. This should include specific regulations and incentives for in-conduit hydropower.
- Invest in Capacity Building: Prioritize training and skill development programs for Libyan engineers and technicians in the specialized areas of in-pipe hydropower installation, operation, and maintenance to ensure local ownership and sustainability of the project.
- Seek International Partnerships: Actively pursue collaborations with international technology providers and financial institutions to leverage expertise, secure funding, and ensure access to advanced turbine technologies and critical spare parts.
- Prioritize Infrastructure Resilience: Recognize in-pipe hydropower as a key component of a broader strategy to enhance the resilience and operational autonomy of critical national infrastructure, reducing vulnerabilities to external disruptions and improving overall national security.
- Quantify Holistic Benefits: Beyond direct electricity generation, rigorously quantify and communicate the full spectrum of benefits, including reduced water loss, extended infrastructure lifespan, and improved operational efficiency, to justify investment and inform public perception.

Through embracing this integrated approach, Libya can transform its monumental Great Man-Made River Project into a beacon of sustainable development, securing both its water and energy future in a challenging global landscape.

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