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Unlocking Hydropower's Potential: Retrofitting Infrastructure and Harnessing Unconventional Sources for Clean Energy Transitions

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Abstract

Hydropower holds a pivotal role within the water-energy nexus for facilitating the clean energy transition, particularly in unconventional and retrofit opportunities. As a renewable energy source, hydropower contributes to decarbonizing the energy sector while simultaneously supporting water management objectives. By integrating hydropower generation into existing infrastructure such as water supply systems, weirs, irrigation networks, and wastewater treatment facilities, synergies can be leveraged to optimize resource utilization and enhance system resilience. This further offers some options for diversifying the electricity mix and speeding up the clean energy transition. However, the complex interaction between water availability and energy production necessitates careful planning and adaptive strategies to mitigate risks associated with climate variability and changing demand patterns. Unlocking the potential of hydropower through these unconventional and retrofitting opportunities is thus instrumental in advancing sustainability goals and ensuring the success of clean energy transitions in the face of various challenges. By leveraging existing infrastructure and exploring innovative solutions, countries stand to significantly enhance its energy resilience and reduce its carbon footprint. Moreover, such initiatives align with broader international objectives, including the Paris Agreement's vision of transitioning to a zero-emission society by 2050 and the European Union's FIT for 55 targets. Under these considerations, this paper seeks to explore the potential of retrofitting existing infrastructure and harnessing unconventional hydropower sources with examples in Czechia, South Africa and Türkiye to address electricity shortages, mitigate carbon emissions, and contribute to the broader clean energy transition agenda. The insights gained from this analysis can inform policy frameworks, investment strategies, and technological innovations aimed at fostering sustainable energy practices.

keywords: *hydropower, retrofitting, digitalization, innovation*

1. Introduction

Energy sustains global economic and social development and given the current state of energy shortages in many countries and the international focus on reducing CO_2 emissions, the development of renewable and sustainable resources has become a top priority. Water and energy are two of the most important resources required for the sustainability and growth of cities and countries. The opportunities and multiple benefits of integrated water and energy resource management are not new. The advantages associated with the generation of hydropower can be attributed to the water-energy nexus [1] principle. This principle describes the directly proportional relationship between energy use and water demand and therefore the need to explore methods in which water and energy supply can be coupled. A good example of this is hydropower generation through the integration of hydropower technologies into existing infrastructure where excess pressure exists [2]. There is considerable energy consumption associated with urban water supply systems, which represents approximately 7% of the world's energy demands [3]. Studies have identified possible locations within existing water infrastructure for energy recovery. The choice of appropriate turbine/generator unit(s) for installation will mainly be determined by the physical attributes of different types of hydraulic structures, in combination with the available net head and water flow information [4]. **Figure 1** illustrates different areas that may have the potential for hydropower (with examples depicted in **Table 1**).

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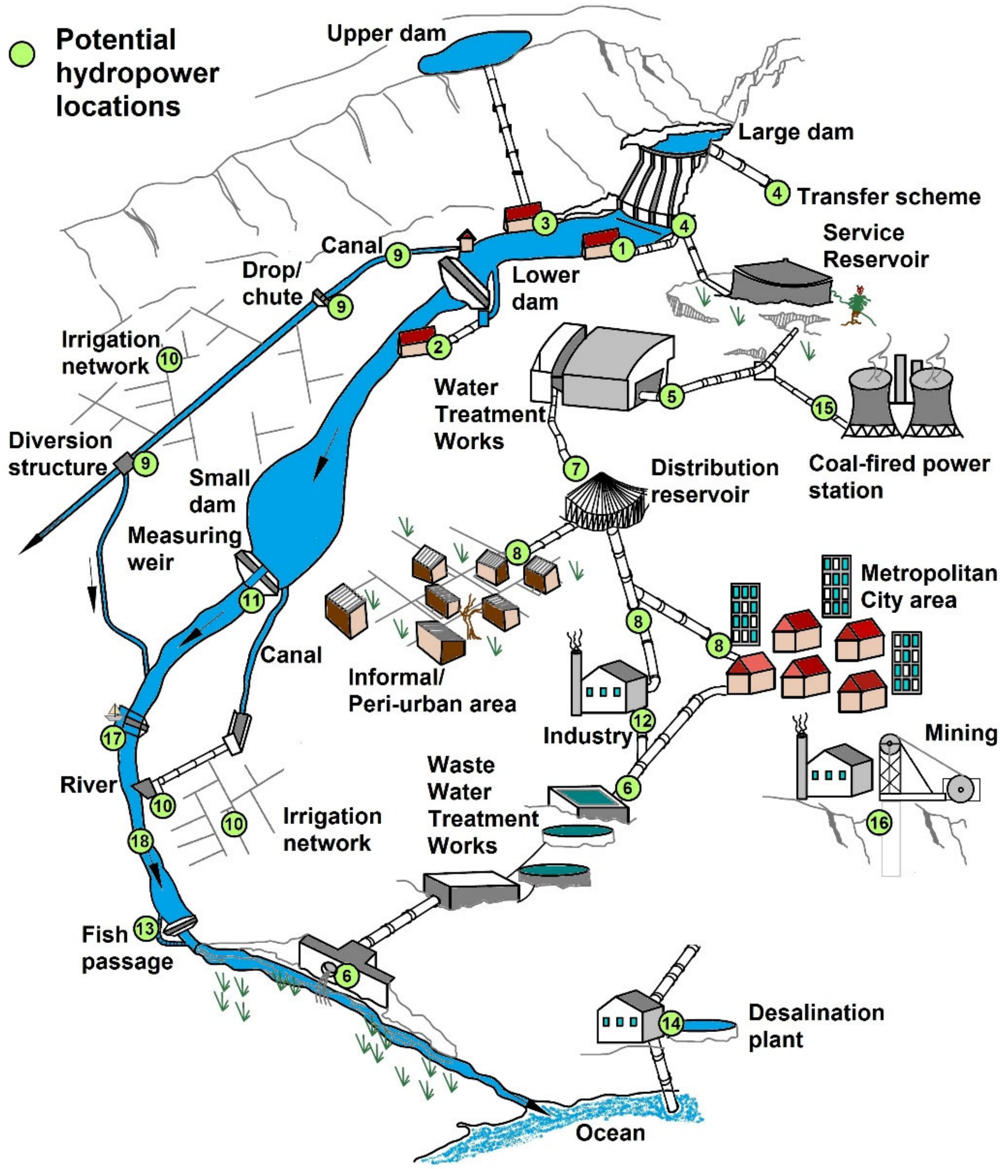

Figure 1: Potential locations for hydropower energy-generation (adapted from [4])

Table 1: Hydropower plant types(# linked to Figure 1, adapted from [5] & [6])

① **Storage schemes**	② **Run-of-river schemes**	③ **Pumped storage schemes**
		
Gariep Dam, South Africa (SA) (4 x 90 MW Francis turbines)	Collywobbles on Mbhashe River, SA (3 x 14.4 MW Francis turbines)	Ingula's upper Bedford Dam, SA intake feeding 4 x 333 MW pump-turbines

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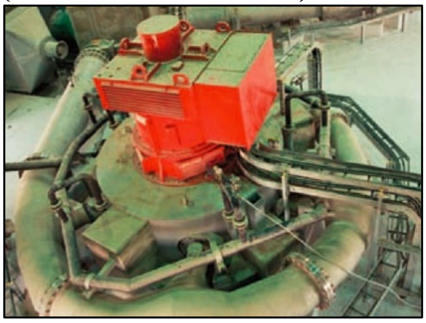
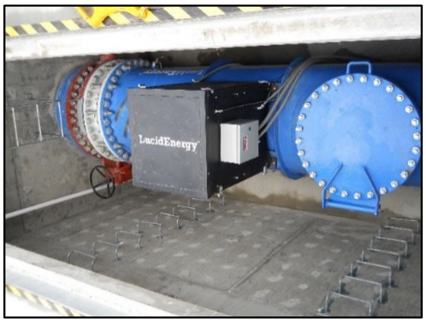
④ Dam releases (into raw water supply system or transfer schemes)  Francis turbine (600 kW) in the OFT Transfer Scheme, SA	**⑤Water Treatment Plant (raw water)**  Wemmershoek, SA (2 x 130 kW Francis)	**⑥ Waste Water Treatment Plant (inflow or effluent outflow)**  Pelton turbines (2 x 830 kW) Amman City, As-Samra plant (Jordan) [6]
⑦ Potable water at reservoirs (pressure-reducing stations (PRS)) or bulk supply system  Crossflow turbine (96 kW) installed in bulk supply line, Bloemwater, SA	**⑧ Potable water flowing in the network or at PRS**  Inline 20 kW spherical turbine, Riverside, Los Angeles, USA	**⑨ Irrigation canals or water tranfer channels**  Kinetic 5 kW turbine in Boegoeberg irrigation canal, SA
⑩ Irrigation network  PAT (3 x 120 kW) installation on irrigation network, Utah, USA [7]	**⑪ Weirs**  Beeston Hydro on the River Trent (1.66 MW), Nottinghamshire, UK [8]	**⑪ Industrial uses/outflows**  Potential 97 kW hydro installation at Abalone farm outlet, Gansbaai, SA

⑬ Fish (pass system) ladders  Installation on attraction discharge at fish pass entrance (348 kW Francis turbine), Aire-La-Ville, Switzerland [6]	**⑭ Desalination plants**  Pelton turbine, the motor and the pump, Tordera, Spain [6]	**⑮ Energy-generation systems (raw water lines, cooling or heating)**  75 kW Francis turbine installed in cooling system in a biomass plant, Sangüesa, Navarra, Spain [6]
⑯ Mining sector  3CPS installation Ikamva, Sibanye Gold's Kloof no. 4 shaft, SA	**⑰ Navigation locks and dams**  Marcinelle power plant, 2 x 325 kW VLH turbines, Sambre River, Belgium [6]	**⑱ Rivers**  Kinetic turbine (5 kW) installed in river Akwanga, Nigeria

Many countries worldwide are confronted with an energy crisis that highlights the significance of exploring all viable renewable energy sources. Hydropower offers the prospect for economic expansion and for achieving the Sustainable Development Goals (SDGs) set by the United Nations. In the past, hydropower has typically been harnessed at large dams, where the outlet flow is used to generate electricity through turbines. Another conventional hydropower installation would be run-of-river schemes where water is diverted through turbines and released back into the river further downstream. However, as most economically viable large dams have already been developed, attention has turned towards small-scale, mini, and micro-hydropower as alternative means of generating electricity. A number of countries have looked at utilizing existing water infrastructure to create multipurpose hydro schemes [8]. In a study by [8] numerous types of unconventional hydropower developments in Switzerland, Austria, Italy, United Kingdom, France and Spain were referenced, highlighting the increasing incorporation into water infrastructure [8]. Even the smallest water infrastructures, such as those supplying water to homes, have the theoretical potential to generate hydropower.

In Massachusetts in the United States of America (USA), there are over 600 public water systems and publicly owned treatment works or wastewater facilities that may be able to take advantage of a conduit hydropower system [9]. A study conducted by Oak Ridge National Laboratory [10], identified significant conduit hydropower opportunities to enhance renewable energy portfolios in the USA while also improving the energy efficiency of water delivery systems. The U.S. Department of the Interior Bureau of Reclamation conducted a study in 2012 on reclamation-owned conduits and found that 191 of the 530 conduits analyzed, had at least some level of hydropower potential, and that 70 of those sites evaluated could be economically feasible for development [11].

Researchers developed an algorithm to assess the hydropower potential and energy recovery in a water distribution system based on the total available energy and evaluated the city of Fribourg in Switzerland which showed that there is approximately 170 MWh/year of energy unutilized in the network and a further 430 MWh/year which could be extracted from the system at the PRSs [12]. Hydraulic software called EPANET was used to identify hydropower potential in water distribution systems in the Alpine regions in Austria [13]. There are thus a growing number of countries worldwide identifying, evaluating and incorporating hydropower into their water infrastructure.

2. Harnessing and unlocking hydropower potential

The absence of national goals for hydropower development in many countries is often a reflection of the varying priorities, resources, and policy landscapes that influence energy strategies globally. While hydropower remains a key component of the global renewable energy mix, it is not always a priority for all countries due to a combination of geographic limitations, economic constraints, environmental concerns, competition from other renewables, and policy gaps. In many instances, countries may choose to pursue energy sources that align more closely with their national contexts, resources, and sustainability goals, which explains why hydropower may not always feature prominently in their national energy strategies. This however does not mean that there are not viable opportunities that could be explored.

2.1 Czechia perspective on unlocking hydropower potential

Czech Republic is an inland country in the centre of Europe, which is drained by four major rivers into three seas (Black, Baltic, North). All of the rivers start in the Czech Republic, which means that the country solely relies on precipitation as its water source and the river flow rates are low or moderate. The hydrology situation is reflected in hydropower development. Both total installed power and generated electricity are relatively small compared to other sources (thermal, nuclear, photovoltaic).

The total installed power in hydropower plants in the Czech Republic is 2.2 GW (more than half is installed in pump storage power plants, PSPP) and energy annually produced is around 2.5 GWh (around 350 GWh in PSPP). Production of small hydropower plants with installed power below 1 MW is 500 GWh. Overall hydropower plants only contribute about 2% to the national energy production.

Most of the bigger hydropower plants (> 10 MW) are situated along river Vltava and are operated by company CEZ, the major electricity producer in the Czech Republic underscoring the relatively small scale of the Czech hydropower market compared to its European counterparts. The principal role of Czech hydropower is in maintenance of grid stability and energy accumulation. The country is focused on integrating hydropower within its broader energy transition strategy, aiming to balance renewable energy production with environmental sustainability. The development of small, unconventional hydropower plants in urban water systems, irrigation networks, and waste water facilities offers potential for growth.

Currently there is no significant hydroelectric potential to be technically exploited in new power plants. However, a significant portion of the hydropower potential is being unlocked through the comprehensive modernization of existing hydroelectric power plants. Investment of approximately CZK 3 billion (EUR 120 million) over the last 15 years in upgrading over twenty large, small, and pumped-storage hydroelectric power plants meant not only increased capacity, but also improvement of regulation ability. The Czech Republic also invests in pumped-storage hydroelectric power plants, which play a crucial role in energy storage and management, especially for balancing the variability of renewable energy sources like wind and solar. These facilities are vital for energy security and managing peak electricity demands.

A good example of current activities is hydropower plant Orlik (nowadays 4x90 MW in Kaplan turbines, head 70.6 meters), which is planned to be converted into a combination of peaking hydropower plant (2x90 MW Francis turbines) and pump storage power plant (2x90 MW pump turbines). Whole renovation will be done just by replacing the mechanical and electrical parts. Since it is already existing hydropower plant and there will be no significant new civil works the process acquiring all environmental permissions is much easier.

Ideas of building three new pump storage power plants are presently discussed to enhance the grid stability in future volatile energy market. Regarding the small energy sources currently there are more than 550 small hydropower plants in operation, 60% of them with power output below 100 kW [14]. New small hydropower plants are being built in water treatment plants in accordance with EU legislation which pushes full self-consumption in the water treatment sector achieved by combination of renewable sources (hydro, solar, biogas, wind). According to [15] there are no other ongoing small hydropower projects or concrete plans for any additional small hydropower development.

2.2 South African perspective on unlocking hydropower potential

The African continent has amongst the largest unexploited potential for hydropower growth in the world and has the prospect to be the first continent to develop its economy using sustainable renewable energy [16]. In 2022, Africa generated 150 TWh of hydropower, had a total installed capacity of 40 GW (which includes pumped storage), but only added 1860 MW of new hydropower capacity [17]. Certain countries such as the Democratic Republic of the Congo have great hydropower potential while the potential in other African countries such as South Africa (SA) is much less. The reason for this is due to SA being a water-scarce country and consequently, it does not have the greatest hydropower potential. SA has developed extensive water infrastructure to store sufficient water and transfer it to the consumers in various conduits. In a study in [18], it is investigated how existing infrastructure could be retrofitted as well as harnessing some of the unconventional sources as illustrated in **Figure 1.**

The study also resulted in the compilation of a hydropower atlas for SA which included some of these unconventional hydropower opportunities and from which the overall potential for SA could be estimated [18]:

- Total conduit hydropower potential of approximately 183 MW from 919 assessed sites (excludes water distribution networks);
- Total hydropower of 1102 MW from 654 analyzed storage schemes (non-powered dams);
- Total hydropower potential of 10.7 MW – 13.7 MW from 124 Waste Water Treatment Plants (WWTPs);
- Total hydropower potential of 10.67 MW – 13.3 MW from 122 Water Treatment Plants (WTPs);
- Total hydropower potential of 10.6 – 50.3 MW from 424 gauging weirs; and
- Total hydropower potential of 22 MW in primary transfer schemes.

Due to the complex interplay between water availability and energy production, meticulous planning and adaptive strategies are required to mitigate risks associated with climate variability and changing demand patterns. Harnessing the potential of hydropower from existing infrastructure provides another opportunity in advancing sustainability goals and ensuring the viability of clean energy transitions in the face of multifaceted challenges.

2.3 Turkish perspective on unlocking hydropower potential

Türkiye ranks the second in Europe considering the installed power capacity of hydropower with 32.5 GW. Türkiye has 2.3 GW of hydropower projects currently under development, of which 460 MW are under construction [19]. There are 146 large reservoir hydropower plants and 616 run-of-river type hydropower plants in Türkiye [20]. There exists no pumped storage type hydropower plant. In 2035, the total installed capacity is expected to exceed 35 GW [21].

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Türkiye has set various goals and objectives regarding the exploitation of its hydroelectric potential. Türkiye aims at increasing its installed hydroelectric capacity to meet the increasing energy demand and reduce dependence on imported energy sources. Türkiye has seen rapid development in hydropower over the past few decades, but as available hydropower sites become more limited and environmental concerns increase, further expansion may have more stringent environmental regulations and complex approval processes. The pace of development could be influenced by such regulatory and environmental safeguards. At the same time, it's worth noting that technological advancements, particularly in efficiency and innovation in hydropower, could help offset some of these challenges.

Specific targets for capacity expansion are often outlined in government strategic energy plans. Considering the age of large hydropower fleet, modernization and rehabilitation of existing hydroelectric facilities to increase efficiency, reliability and environmental performance is another concern for hydropower in Türkiye. This includes upgrading equipment, implementing new technologies and ensuring compliance with existing regulations. Hydropower plays an important role in Türkiye's broader renewable energy strategy, which aims to increase the share of renewable energy in its energy mix. The integration of hydroelectric energy with other renewable sources such as wind and solar is planned to ensure a balanced and sustainable energy portfolio. Another issue that has come to the fore recently is the use of hydroelectric potential in the drinking water network.

Hydro units installed in parallel to the equipment that reduces the excess pressure in the drinking water network through friction enable municipalities benefit more from the water-energy nexus with the approach of green energy transformation and distributed generation.

In **Figure 2**, the geographical information of pipes and nodes of a large city is generically depicted. There exist 12 recovery locations with PRVs. The total capacity of these recovery points is calculated as 3.5 MW. However, the capacity factors of hydropower units in drinking water systems are positively different compared to the values of traditional hydropower plants. One pilot project in drinking water system in Türkiye has 67% capacity factor meaning that the power plant operates at full load during 67% of the whole year.

The planned capacity increase will be achieved through installing new hydropower plants, e.g., 2.3 GW of new projects. The incorporation of hydropower in drinking water supply networks is not considered in the long-term planning yet. Some pilot installations such as the ones in this paper are being validated. No WWTPs to be reported in the country.

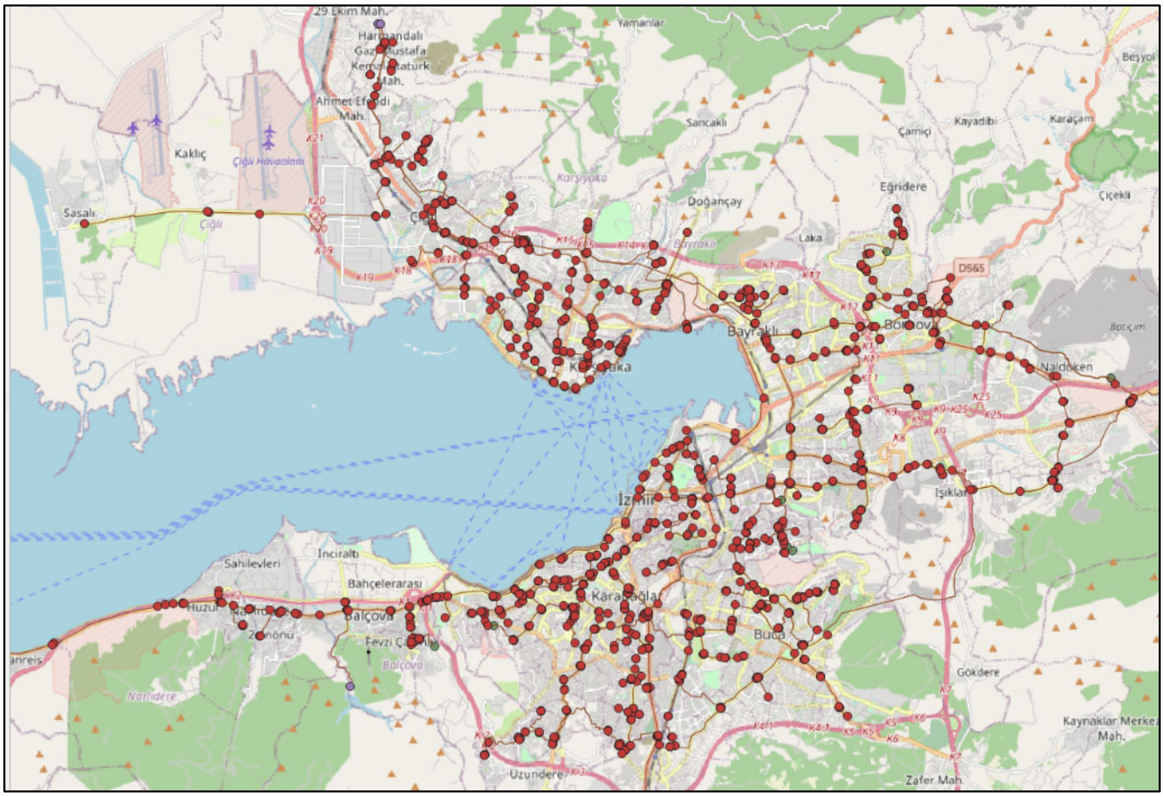

Figure 2: Drinking water system of a large city with population > 5 M inhabitants (dots are nodes; lines are pipes)

3. Examples of unlocking unconventional hydropower potential

Czechia, South Africa, and Türkiye are exploring unconventional hydropower opportunities to enhance energy sustainability. Czechia focuses on modernizing existing plants and developing small-scale hydropower in urban and water systems. South Africa targets retrofitting existing infrastructure like storage schemes and water treatment plants for hydropower, compensating for its water scarcity. Türkiye, with significant hydropower capacity, is exploring hydropower in drinking water networks and upgrading its existing fleet to increase efficiency and reliability while balancing environmental concerns.

3.1 Examples in Czechia

Examples of unlocking hydropower potential and also an example of water-energy nexus are two small hydropower plants installed within water infrastructure sector in the Czech Republic. Water industry sector is an important energy consumer. Electrical energy is used for different processes, water pumping being the most power consuming one (see **Figure 3**).

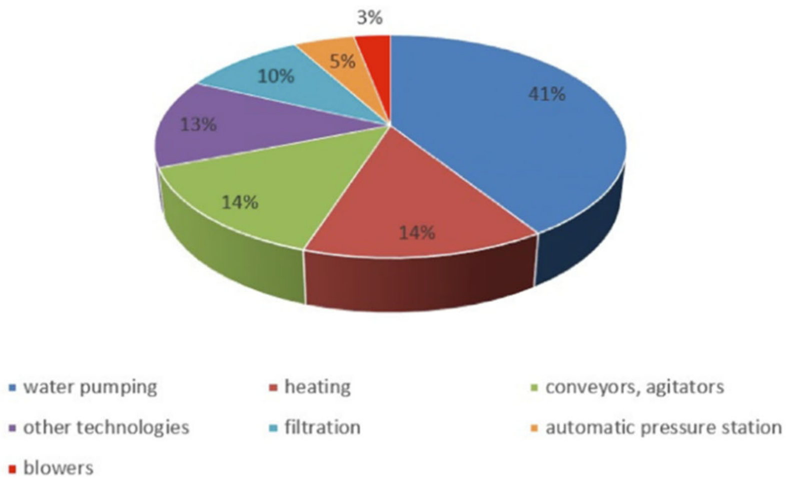

Figure 3: Energy consumption in water treatment plant (adopted from [22])

Electrical energy is used by many devices (pumps, blowers, valves, etc) and also measurement sensors (see **Figure 4**). However, hydropower turbines can be installed within the water treatment process to recover some of this energy from pressurized flows or elevation differences. This is especially relevant in situations where water needs to be moved from lower to higher elevations or where high pressure in the system must be reduced. By harnessing this energy that would otherwise be lost, water treatment plants can produce electricity and reduce their reliance on external power sources, contributing to both energy efficiency and cost savings.

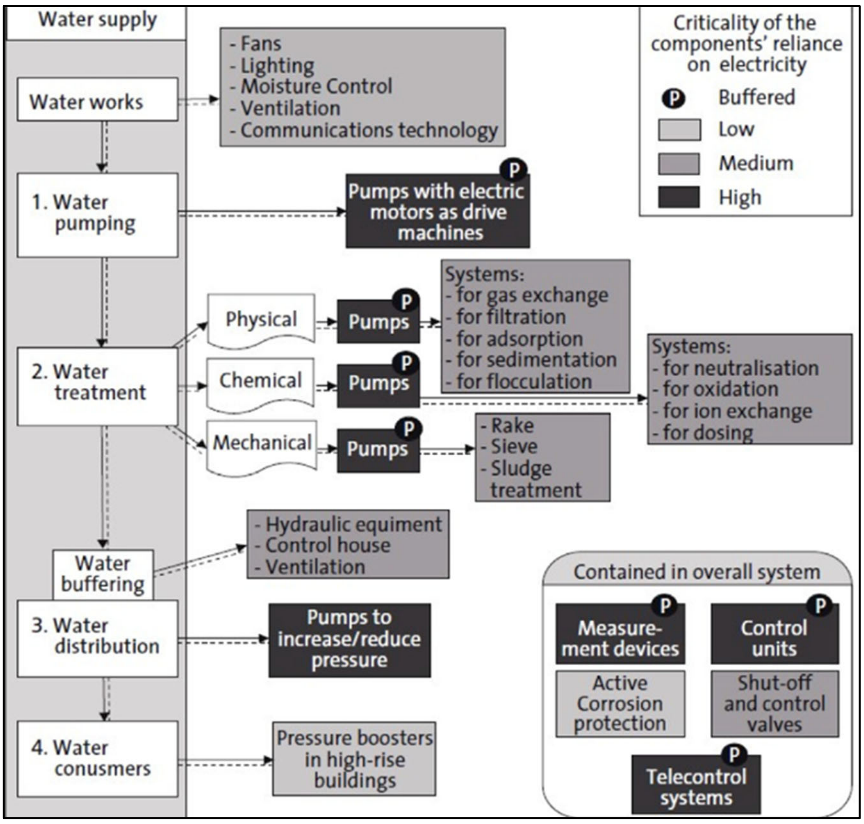

Figure 4: Energy consuming devices in water treatment plant (adopted from [23])

3.1.1 Small hydropower plant in waste water treatment plant Blansko

Geomorphology of the landscape of a small town Blansko, which is located in a narrow valley, did not allow to build the WWTP at the town outskirts, but on the flat land above the town. The sludge must be pumped up the hill where it is treated and then the clean water runs down to the river.

In 2022 a small water hydropower plant was built close to the river, which utilizes 26 m of the gross head using 300 mm diameter penstock (**Figure 5**) and flow rate 50 l/s. Two pumps in turbine mode (PAT), see **Figure 6**, are installed, each with power output 10.3 kW (one PAT is a backup in case of accident or repair). Installation of the hydropower plant is part of a bigger investment plant at this wastewater treatment plant which includes also a new photovoltaic power plant and biogas cogeneration unit.

Figure 5: Two penstocks of Blansko small hydropower plant: DN300 (clean water from WWTP to small hydropower plant), DN400 (sludge from pumping station to WWTP)

The layout at Blansko WWTP is more of an exception than a standard practice, primarily due to the unique geomorphology of the area. Most WWTPs are located on flat land near rivers to facilitate gravity-fed systems and minimize energy consumption. The setup in Blansko, which utilizes pumps in turbine mode (PAT) for energy recovery, is a creative solution to the site's geographical constraints. The potential for energy recovery in WWTPs is significant, particularly in plants that have elevation differences between water inflow and outflow.

Figure 6: Two pumps in turbine mode (volute one-stage pumps, both rotor and stator parts from stainless steel, mechanical stainless-steel seal, asynchronous generator)

3.1.2 Small hydropower plant in water treatment plant Vyšní Lhoty

This small hydropower plant utilizes potential of the water distribution conduit between Morávka dam and water treatment plant (WTP) in Vyšní Lhoty [14]. There are 3 pumps in turbine mode installed (PAT) with rated power outputs, 90 kW, 110 kW and 132 kW (see **Figure 7**). Return of investment for similar projects is 2 to 5 years, which makes them an attractive option for water distribution companies and municipalities.

Figure 7: Small hydropower plant installed on raw water conduit in Vyšní Lhoty [14]

3.2 Examples in South Africa

To showcase the typical opportunity which can be exploited using existing infrastructure two examples in South Africa is discussed in the sections below (conduit hydropower plant development and the retrofitting of a non-powered dam).

3.2.1 Conduit hydropower plant development

According to a study done by [12] the city of Fribourg in Switzerland has a conduit hydropower potential of nearly 600 MWh/a of which the PRSs has 430 MWh/a potential. Numerous other researchers have also investigated the conduit hydropower potential which exists in water and irrigation distribution systems [24]-[30]. Many studies demonstrated the economic and environmental benefits of energy recovery systems implemented in water supply and water distribution systems [2], [31]-[35]. The studies demonstrated that the financial benefits, either from energy sales and/or reduced operational costs, resulted in acceptable payback periods [24],[25],[31]. These benefits are even more noteworthy in countries such as SA, which have been facing high tariff hikes since 2008 (with some years increases greater than 20%). There exist opportunities for municipalities, water utilities, large water consuming industries and mines, to consider the implementation of small-scale hydropower installations. Conveyance systems must be operated effectively to ensure sustainable water supply, which must be carefully managed when conduit hydropower is also considered. The generated hydroelectric energy could be used for the onsite demand, supplying an isolated mini grid or fed into the national electricity grid.

The advantage of the this hydropower generation application is that it requires minimal civil works with predominantly positive environmental and social impacts with most sites being viable as existing infrastructure is utilized. As an example, the Caledon-Bloemfontein potable water supply system supplies the majority of the water to the Bloemfontein area in SA. The supply system has a design capacity of 141 Ml/day with treated water pumped to the De Hoek reservoir from where it gravitates through an 1168 mm Ø pre-stressed concrete gravity main to the Uitkijk break water reservoir and then further to the Brandkop Reservoir, see longitudinal profile of gravity section in **Figure 8**.

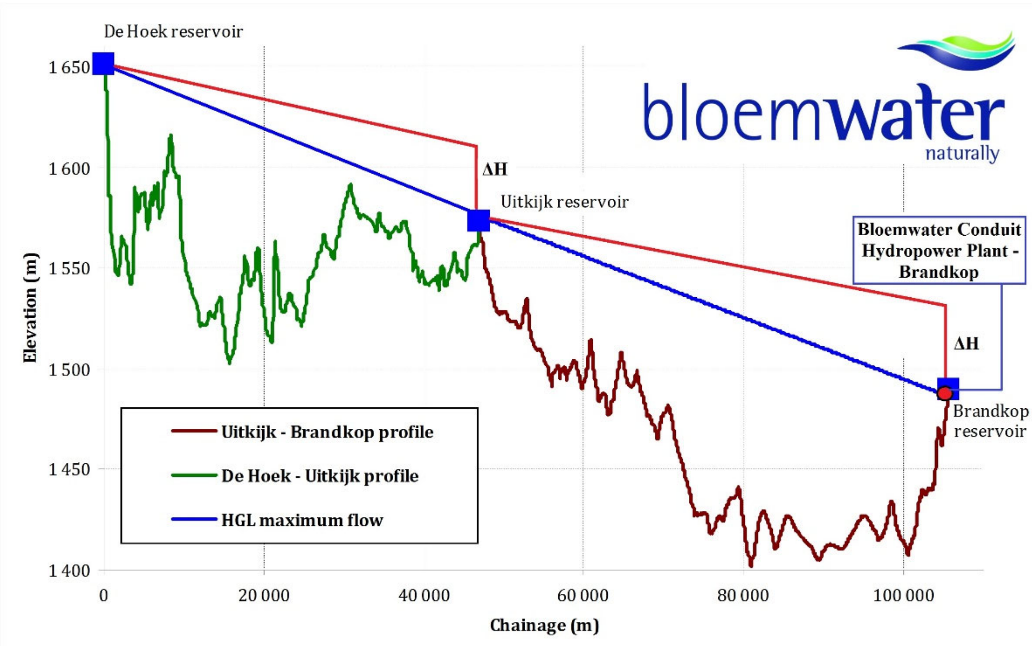

Figure 8: Longitudinal profile of Caledon-Bloemfontein pipeline with hydraulic gradelines [5]

Excess energy is dissipated through PRVs located upstream of the Uitkijk and Brandkop reservoirs, before being discharged into the reservoirs. A hydraulic assessment of the pipelines was conducted over several months recording the available pressure head and flow rates. The results indicated that approximately 350 to 400 kW of potential energy is available at each of these reservoir sites.

As a first phase, Bloemwater decided to develop a hydropower plant with enough capacity to meet the electricity demand of their head office located at the Brandkop Reservoir. The available power generation was compared with the electricity consumption data to select the optimal installation configuration and turbine to meet the demand. Based on this only a portion (±30% on average of the water supplied) is diverted to the turbine (0.35 m^3/s at an average pressure of 40 m pressure head. A 96 kW crossflow (Banki) turbine with synchronous generator was selected for this application, see **Figure 9** [25]. Electronic regulators are connected to provide the dissipating capability and also keeps the voltage and frequency stable. The hydropower plant generates enough renewable electricity to meet the peak demand of Bloemwater's head office and the electricity needs of the reservoir site. Theoretical annual energy production, based on average flow and pressure values, is estimated at 837 500 kWh.

Figure 9: Brandkop Conduit Hydropower Plant (SA)

The feasibility study for this installation assumed a design life of 40 years, an electricity escalation rate of 8%, and a 7% discount rate on Bloemwater's investment. Based on historical utility costs, the payback period was estimated at approximately 6 years. The system's success and quick payback have encouraged Bloemwater to plan for the next phase and explore other conduit hydropower opportunities. However, the plant currently operates below its full potential, as the peak 96 kW is only needed during peak demand hours. During off-peak periods and weekends, it runs at just 30% capacity, presenting an opportunity for more efficient utilization.

This synergy between water and energy operations has allowed Bloemwater to optimize the system for greater efficiency. Since its launch in 2015, the plant has reliably supplied Bloemwater with hydroelectric power even during load shedding. The water supply from the WTWP, the pipeline system's characteristics, the Brandkop reservoir's demand, and the head office's electricity needs now function as an integrated system. This synergy between water and energy operations has allowed Bloemwater to optimize the system for greater efficiency. YouTube video of this project: *The Power of Hydro: Bloemwater Conduit Hydropower Plant Project* (https://www.youtube.com/watch?v=um4aIk53hrs). A more detailed guideline for the conduit hydropower development and this specific pilot plant can be found in [25] and [34].

3.2.2 Retrofitting non-powered dams

Rather than building dams solely for hydropower existing reservoirs designed for different purposes are being equipped with hydropower plants to meet specific base or peak electricity demands.

While the potential for this form of hydropower is limited by the number of existing dams, its advantages are significant. The energy is readily available to be harnessed, and additional environmental impacts are minimized. This approach is especially beneficial for smaller plants, where constructing a large dam would be impractical [36].
[37] developed a hydropower retrofitting model (HRM) to follow a logical procedure to evaluate the potential to retrofit hydropower at existing dam sites in SA. The model aims to assess financial, environmental and social feasibility at the pre-feasibility stage and provide a recommendation on whether the project warrants further investigation, rather than proceeding to a detailed design.

An example of a dam retrofitting project is the Vaal Dam Hydropower Scheme which is a proposed renewable energy project within the framework of the National Water Act 1998 (NWA), aimed at harnessing the potential energy of the Vaal Dam's releases to generate electricity. This initiative aligns with the NWA's goal of sustainable water use and equitable access. In April 2023, the Department of Water and Sanitation (DWS) issued a Request for Water Use License (WUL) Applications for Hydropower Generation to enable renewable energy projects, specifically independent hydropower generation.

The Vaal Dam, located between the Free State, Gauteng, and Mpumalanga provinces in South Africa, was selected for its strategic position and potential to contribute clean electricity to the local and regional power grid. The hydropower project integrates ecological reserve releases, presenting a sustainable solution to energy needs while optimizing water resource management. The primary objective of the Vaal Dam Hydropower Scheme is to retrofit the dam's outlet works with turbines to convert the potential energy in the dam's stored water into electricity. The project aims to generate a total power of 4324 kW. The Vaal Dam, built in 1938 and raised twice to its current capacity of 2575 million m^3, consists of a concrete gravity structure with an earth-fill section. The dam has a significant catchment area of 38505 km^2 and serves as a critical water source for the region. The existing outlet works, comprising eight 900 mm sleeve valves, will be retrofitted to accommodate the new turbines.

The project considered three options for turbine installation, with Option 2 being the preferred choice:

- Option 1 - Removing four lower sleeve valves, reinstalling these at a higher level, and installing four turbines.
- Option 2- Removing four sleeve valves, reinstalling them at a higher level, and installing two larger turbines (see **Figure 10**).
- Option 3- Utilizing four unused outlets, connecting them to new outlet pipes leading to a new turbine room outside the flood line on the right bank downstream of the dam wall.

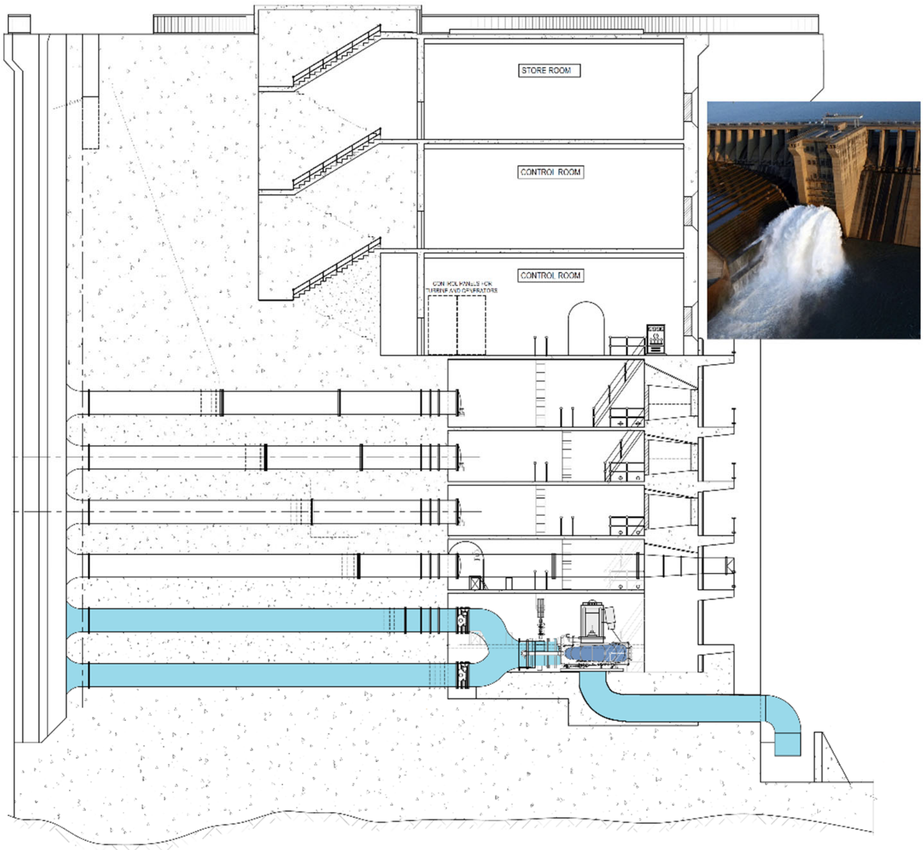

Figure 10: Conceptual layout of retrofitted turbine installation

The turbines, vertical Francis type, will use the river's ecological releases to generate hydroelectric energy, with water discharged into a newly constructed stilling basin after pressure dissipation. The hydraulic analysis examined the Vaal Dam's catchment area, historical water uses, and using historical flow records from a gauging site constructed the flow duration curve. The technical characteristics of this site are provided in **Table 2**.

Table 2: Technical characteristics of Vaal Dam application

Description	**River release**
Total discharge	16.24 m³/s
Net head	32.6 m
Number of turbines	2 x vertical Francis
Rated speed	250 rpm
Velocities in penstocks	3.31 m/s
Maximum turbine power	2283 kW
Total maximum turbine power	4566 kW
Peak efficiency	89.7 %
Maximum electrical power	2162 kW
Total maximum electrical power	4324 kW
Annual power generation*	29.82 GWh

* Base on the average generating capacity of the historical flow and water level data

The Vaal Dam Hydropower Scheme represents a forward-looking initiative that addresses energy needs while prioritizing responsible water resource management. By retrofitting the existing dam outlet structure with hydropower turbines, the project aims to generate clean and renewable electricity, contributing to national energy diversification and environmental sustainability. The detailed technical design ensures the project's stability, safety, and longevity, reflecting a commitment to meet rising energy demands and embracing a future where clean energy and water resource management coalesce for the benefit of present and future generations.

3.3 Examples in Türkiye

Two different demo projects in Turkey can be given as examples of generating electricity in the drinking water system. The first of these is the IZSU Karabaglar P11 Hydropower Plant (HPP), located within the borders of Izmir province. The second is DESKI Akbas HPP, located within the borders of Denizli province. Among the power plants whose technical specifications are given below (**Table 3**), P11 HPP has an installed power of 535 kW (**Figure 11**), while Akbas HPP has an installed power of 2.3 MW (**Figure 12**). In **Figure 11-a,** P11 POMPA IST. is the location of the pumps in **Figure 11-b.** Also, ONERILEN HES YERI is the planned location of the P11 HPP. ODA and T-13 DEPO are locations of the pressure reducing valve and the tank. **Figure 11-c** is the outgoing pipe of the pumping station. In **Figure 11-a**, it is intended to emphasize that the pump station and power plant are located in the middle of the city, within living spaces.

Table 3: Technical Characteristics of Pilot Applications

Parameter	P11 HPP	Akbas HPP
Number of Units	1 Unit	1 Unit
Turbine Type	Horizontal Francis with PRV	Vertical Pelton
Turbine Design Flow	860 l/s	1200 l/s
Net Head	70 m	235 m
Optimum Turbine Efficiency	90.6%	92%
Power at Optimum Efficiency	535 kW	2300 kW
Rated Speed	1500 rpm	750 rpm

Figure 11: IZSU Karabaglar P11 Hydropower Plant (Türkiye)

The IZSU Karabaglar P11 Hydropower Plant is a key example of integrating small hydropower generation into an existing drinking water system. It uses a horizontal Francis turbine with a PRV to harness the energy from excess pressure in the water distribution network. This type of installation is crucial for its dual functionality, as it not only generates electricity but also regulates pressure within the water system, ensuring the safety and efficiency of the water supply.

The relevance of this case study lies in its demonstration of how energy recovery through hydropower can be applied to urban water systems, where maintaining appropriate pressure levels is a necessity. It showcases an innovative way to generate renewable energy without affecting the operational efficiency of critical infrastructure such as drinking water distribution. Moreover, it highlights the potential of replicating similar projects in other urban areas, thereby contributing to local energy resilience and decarbonization efforts.

Akbas HPP Project is a pilot project for replacing a PRV to serve the water for irrigation and drinking water treatment. This is first installation in the Egean Region with about 250 m head and Pelton type turbine with 6 nozzles. The continuity of service is very critical here because the water going out of the turbine is being used for irrigation and drinking water system. Also, the changing demand is very challenging since the power plant will be operated considering the tailwater level in the outgoing pool.

This case study is relevant because it demonstrates the technical challenges and solutions involved in incorporating hydropower into a water system with dual usage drinking and irrigation. The use of a Pelton turbine, suitable for high head conditions, shows how hydropower systems can be customized based on specific site conditions. The project's success also highlights the importance of continuity of service, ensuring that water needs are met while generating renewable energy.

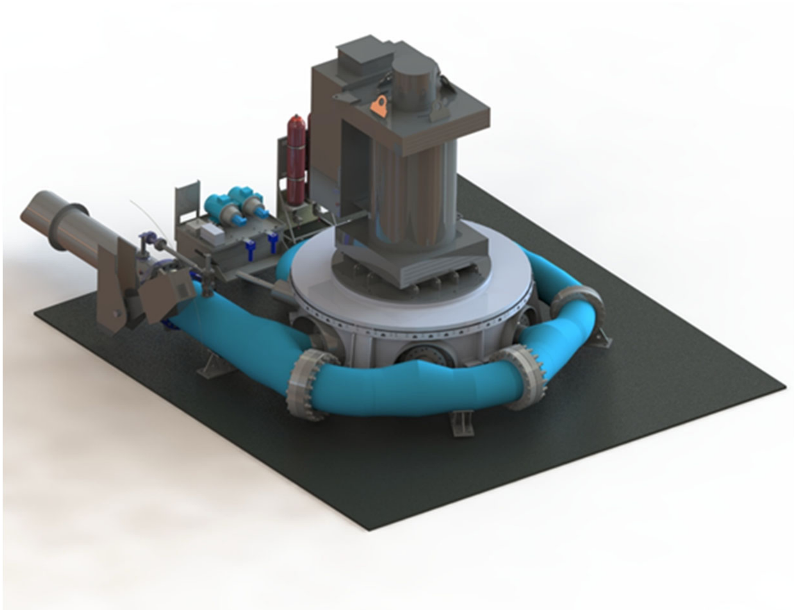

Figure 12: DESKI Akbas HPP (Türkiye)

4. Conclusion

At present the most favorable hydropower development potential lies within the spheres of rehabilitation/upgrade of plants, conduit hydropower from bulk water supply and distribution systems and transfer schemes, at WWTP and WTP and the hydropower which could be developed at existing storage dams. What all of these developments have in common is that existing water infrastructure is utilized to derive a secondary benefit from these.

These are examples of innovative research being translated into practical, implementable projects. Conduit hydropower leverages existing water supply and distribution infrastructure, enabling the generation of hydroelectric energy as long as there is water demand. Similarly flow into a WTP or from a WWTP could be utilized to generate hydroelectric power.

As these types of hydropower "piggy backs" onto existing water infrastructure it has minimal environmental impact. However, effective operation requires a better understanding of the entire system. Retrofitting an existing dam with hydropower, utilizing the ecological or irrigation releases and the head provides very viable opportunities that could provide reliable, constant base load electricity.

The integration of hydropower into existing water infrastructure does still require further research and development such as:

- Quantification of the potential – Research has shown that not many countries have quantified these unconventional hydropower opportunities and thus it would not be possible to estimate the total generation potential [10], [11] & [18].
- Site suitability assessments - Identifying suitable sites (WWTP, WTP, weirs, dams, water supply systems) with the necessary elevation differences or pressure conditions for hydropower as well as use for the generated electricity.
- Economic viability - Conducting cost-benefit analyses to evaluate the financial incentives for integrating small hydropower plants into water infrastructure.
- Optimization of hydropower applications - Enhancing the efficiency and adaptability of for example PATs in the context of wastewater flows or water distribution systems, which may vary significantly in volume and quality.
- Energy storage/balancing solutions - Investigating how to store or balance the intermittent energy produced from small hydropower within the context of the electricity use pattern or WWTP operations.

There are also challenges with the development of these unconventional hydropower opportunities which include:

- Variable flow rates - Wastewater flow rates or the demand in a water distribution network fluctuate throughout the day, requiring robust control systems to maintain optimal power generation.
- Water quality - The presence of solids or contaminants in treated water can cause wear and tear on hydropower components like turbines or seals in for example WWTP installations.
- Integration with other renewable systems - As sites could include other renewables such as WWTPs incorporating biogas or a dam site including floating photovoltaics, the challenge becomes optimizing the energy mix to ensure reliability and efficient operation.
- Regulatory and permitting issues - Hydropower installations may face regulatory hurdles, particularly in terms of water rights and environmental impacts.
- Financial incentives - The return on investment for small-scale hydropower projects can be long-term, and funding mechanisms or incentives may be required to promote adoption.
- Operational expertise - Many operators at the various water infrastructure sites may not have expertise in hydropower, necessitating specialized training or collaboration with energy professionals.

It is believed that these challenges highlight both the potential and the areas requiring further research and innovation. Addressing these issues will help unlock the broader applicability of hydropower using existing water infrastructure. In the world, there is growing recognition that future economic success is related to engaging a more sustainable economy proactively and, for this reason, national governments and local authorities are compiling Green Economy strategies and action plans [38]. The development of these types of hydropower opportunities as sustainable energy sources fits into these strategies. It is believed that retrofitting infrastructure with hydropower is the "low hanging fruit" in terms of viable renewable energy which could be developed. Hydropower represents a nexus of water and energy and in municipalities, water utilities, and ministerial departments there are several locations where viable hydropower schemes could be implemented.

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References

[1] Gilron J 2014 Water-energy nexus: matching sources and uses *Clean Technol. Environ. Policy* **16** 1471–1479 https://doi.org/10.1007/s10098-014-0853-1

[2] McNabola A, Coughlan P, Williams A P 2014 Energy recovery in the water industry: An assessment of the potential of micro-hydropower *Water Environ. J* **28** 294–304 https://doi.org/10.1111/wej.12046

[3] Coelho B, Andrade-Campos A 2014 Efficiency achievement in water supply systems - A review *Renew. Sustain. Energy Rev.* **30** 59–84 https://doi.org/10.1016/j.rser.2013.09.010

[4] Loots I, Van Dijk M, Barta B, Van Vuuren S J, Bhagwan J N 2015 A review of low head hydropower technologies and applications in a South African context *Renew. Sustain. Energy Rev.* **50** 1254–1268 https://doi.org/10.1016/j.rser.2015.05.064

[5] Van Dijk M, Van Vuuren S J, Barta B 2012 Optimization of energy generation from water supply and distribution systems *In Proceedings of the 2012 HYDRO Conference*, Bilbao, Spain 29–31 October 2012

[6] Shapes 2010 *Energy recovery in existing infrastructures with small hydropower plants multipurpose schemes – Overview and examples* FP6 Project Shapes (work package 5-WP5), European Directorate for Transport and Energy, Brussels, Belgium

[7] Colorado Department of Agriculture (CDA) 2011 *Exploring the viability of low head hydro in Colorado's existing irrigation infrastructure: Final report* Colorado Department of Agriculture, Applegate Group and Colorado State University, Colorado, USA

[8] Choulot A, Denis V, Punys P 2012 Integration of small hydro turbines into existing water infrastructures In Hydropower-practice and application, IntechOpen: London, UK https://doi.org/10.5772/35251

[9] Allen G S, Fay C N, Matys E 2013 *In-conduit hydropower project – Phase I report* ALDEN Research Laboratory, INC Massachusetts Department of Energy and Environmental Affairs, Available online: www.mass.gov/eea/docs/dep/service/energy/hydrop1.pdf [Accessed: 20 July 2024]

[10] Oak Ridge National Laboratory (ORNL) 2014 *Opportunities for energy development in water conduits* ORNL/TM-2014/272 US Department of Energy, Available online: https://info.ornl.gov/sites/publications/Files/Pub50715.pdf [Accessed: 20 July 2024]

[11] US Department of the Interior 2012 *Site inventory and hydropower energy assessment of reclamation-owned conduits* Bureau of Reclamation, Available online: www.usbr.gov/power/CanalReport/FinalReportMarch2012.pdf [Accessed: 20 July 2024]

[12] Samora I, Manso P, Franca M J, Schleiss A J, Ramos H M 2016 Energy recovery using micro-hydropower technology in water supply systems: The case study of the City of Fribourg *Water* **8** 344 https://doi.org/10.3390/w8080344

[13] Möderl M, Sitzenfrei R, Mair M, Jarosch H, Rauch W 2012 Identifying hydropower potential in water distribution systems of Alpine regions. *Proceedings of World Environmental and Water Resources Congress 2012: Crossing Boundaries* 20-24 May 2012 Albuquerque, New Mexico

[14] Goňo M, Kyncl M, Goňo R, 2011 Operating small hydropower plants in water industry sector *Electric Power Engineering* 2011 (in Czech)

[15] UNIDO - ICSHP, 2022. World Small Hydropower Development Report 2022. United Nations Industrial Development Organization, Vienna, Austria; International Center on Small Hydro Power, Hangzhou, China. Available at www.unido.org/WSHPDR2022.

[16] International Hydropower Association (IHA) 2021 *2021 - Hydropower status report - Sector trends and insights,* Available online: www.hydropower.org/resources/publications [Accessed: 18 November 2021]
[17] International Hydropower Association (IHA) 2023 *2023 - World Hydropower Outlook,* Available online: www.hydropower.org/resources/publications [Accessed: 26 July 2023]
[18] Van Dijk M, Hansen C D, Bekker A, Mahamba N N 2022 *The South African Hydropower Atlas* WRC Report project no. K5/2882/3 Water Research Commission, Pretoria, South Africa
[19] International Hydropower Association (IHA) 2024 *2024 - World Hydropower Outlook,* Available online: www.hydropower.org/resources/publications [Accessed: 26 July 2024]
[20] TEİAŞ YTBS. Available online: http://www.ytbs.teias.gov.tr/Eng/Default.aspx [Accessed: 26 June 2024]
[21] Turkish Ministry of Energy and Natural Resources 2024 *Strategic Plan 2019-2023*, Available online: https://sp.enerji.gov.tr/ [Accessed: 01 July 2024]
[22] Kotulla M, Goňo M, Goňo R, Vrzala M, Leonowicz Z, Kłosok-Bazan I, Boguniewicz-Zabłocka J 2022 Renewable Energy Sources as Backup for a Water Treatment Plant *Energies* **15** 6288 https://doi.org/10.3390/en15176288
[23] Petermann T, Bradke H, Lüllmann A, Poetzsch M, Riehm U 2011 *What Happens during a Blackout. Consequences of a Prolonged and Wide-Ranging Power Outage* 1st ed.; BoD: Norderstedt, Germany
[24] Hennig T, Wang W, Feng Y, Ou X, He D 2013 Review of Yunnan's hydropower development. Comparing small and large hydropower projects regarding their environmental implications and socio-economic consequences. *Renew. Sustain. Energy Rev.* **27** 585–595 https://doi.org/10.1016/j.rser.2013.07.023
[25] Van Vuuren S J, Van Dijk M, Loots I 2014 *Conduit Hydropower Pilot Plants* WRC Report No TT596/14 Water Research Commission Pretoria, South Africa
[26] Carravetta A, Fecarotta O, Del Giudic G, Ramos H M 2014 Energy recovery in water systems by PATs: A comparison among the different installation schemes Procedia Eng. 70 275–284 https://doi.org/10.1016/j.proeng.2014.02.031
[27] Vilanova M R N, Balestieri J A P 2014 Energy and hydraulic efficiency in conventional water supply systems Renew. Sustain. Energy Rev. 30 701-714 http://dx.doi.org/10.1016/j.rser.2013.11.024
[28] Butera I, Balestra R 2015 Estimation of the hydropower potential of irrigation networks *Renew. Sustain. Energy Rev.* **48** 140–151 https://doi.org/10.1016/j.rser.2015.03.046
[29] Fontana N, Giugni M, Portolano D 2012 Losses Reduction and Energy Production in Water-Distribution Networks *J. Water Resources Planning and Management* **138** 237–244 https://doi.org/10.1061/(ASCE)WR.1943-5452.0000179
[30] Pérez-Sánchez M, Sánchez-Romero F J, Ramos H M, López-Jiménez P A 2016 Modeling irrigation networks for the quantification of potential energy recovery: A case study *Water* **8** https://doi.org/10.3390/w8060234
[31] Loots I, Van Dijk M, Van Vuuren S J, Bhagwan J N, Kurtz A 2014 Conduit-hydropower potential in the City of Tshwane water distribution system: A discussion of potential applications, financial and other benefits *J. South African Inst. Civ. Eng*. **56** 2–13
[32] White J 2011 Recovering energy from an existing conduit *International Water Power & Dam Construction* June 2011 **63** 18–20
[33] Lisk B, Reekie L, Bloetscher F 2012 Implementing Renewable Energy at Water Utilities *Water Research Foundation*, Denver, USA
[34] Van Vuuren S J, Van Dijk M, Loots I, Barta B, Scharfetter B G 2014 *Conduit Hydropower Development Guide* WRC Report No TT597/14 Water Research Commission, Pretoria, South Africa
[35] Southern Nevada Water Authority (SNWA) 2010 Sustainability in action - 2010 Available online: www.snwa.com/assets/pdf/reports-sustainability.pdf [Accessed on 15 July 2021]

[36] European Small Hydropower Association (ESHA) 2004 Guide on how to develop a small hydropower plant Available online: www.esha.be [Accessed: 15 October 2011]
[37] Van Vuuren S J, Blersch C L, Van Dijk M 2011 Modelling the feasibility of retrofitting hydropower to existing South African dams *Water SA* **37** 679–692 https://doi.org/10.4314/wsa.v37i5.5
[38] Sustainable Energy Africa (SEA) 2017 *Sustainable energy solutions for South African local government: A practical guide* Cape Town: Sustainable Energy Africa Available online: www.sustainable.org.za [Accessed: 1 September 2017]