

## Research Paper

# Opportunities of hidden hydropower technologies towards the energy transition



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## ABSTRACT

Hydropower is the world's most exploited renewable energy source. It provides a substantial, flexible, and reliable source of renewable energy, complementing other renewables like solar and wind power. Besides conventional hydropower potentials and technologies, the development of technologies for the exploitation of hidden hydropower potentials is an ongoing process. This paper presents the current state of hidden hydropower technologies and links them with possible applications in different hydropower potentials. Technologies and potential applications are structured within three main groups (pressurized systems, hydro storage, unpressurized systems), with their mutual interconnections analysed and displayed throughout the paper. The opportunity for the application of hidden hydropower technologies in different roles within the energy system is recognized through the concepts of off- and on-grid roles, the prosumer concept, and on-site measurement powering. This paper shows that hidden hydropower technologies could emerge as significant contributors to a smoother energy transition, especially with the prosumer and off-grid concepts.

## 1. Introduction

Hydropower is the largest renewable energy source globally, contributing significantly to the world's energy capacity (about 20 % according to IEA, 2018). In 2021 hydropower accounted for an impressive 1330 GW of installed capacity worldwide (IHA, 2021). These numbers underline the significant role that hydropower plays in the global energy mix, providing a substantial, flexible and reliable source of renewable energy. Furthermore, the effective complementarity of hydropower with other renewable energies, such as solar and wind power,

is extensively demonstrated (e.g., François et al., 2017; Puspitarini et al., 2020).

The recent legislation within the European Union (EU) emphasizes the importance of decentralized energy production through renewable energy resources. Article 17 of the EU Regulation 2018/2001 underscores the significant contribution of small-scale installations in enhancing public acceptance and implementation of renewable energy, particularly at the local level (EU, 2018). The decentralized energy production, including the utilization of local energy sources, increases energy security, reduces transport distances, and therefore minimizes

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energy losses. The legislation emphasizes that decentralization fosters community development and cohesion at the local level by generating jobs and income opportunities. Moreover, paragraph 4 of Article 15 empowers Member States to consider national measures that encourage a significant increase in self-consumption of energy from renewable sources, reflecting a comprehensive approach to promote renewable energy at the local level fostering sustainability, resilience, and community development within the EU. Article 7 of Regulation 2018/2001 of the European Parliament encourages the establishment of a binding EU renewable energy target for 2030. This would help to further promote the development of renewable energy technologies, provide certainty for investors and give Member States more flexibility to meet their greenhouse gas emission reduction targets as efficiently as possible.

Lately, hidden hydropower in water distribution networks has emerged as a promising renewable energy source. Studies have shown its potential to harness unused energy from water flow in pipelines, reservoirs, and wastewater systems, providing a low-impact means to boost energy generation. Growing interest in using water infrastructure for energy, aligning with global renewable energy goals is apparent.

However, adopting hidden hydropower poses technical and regulatory challenges. On the technical side, integrating turbines into water networks requires managing variable flow rates, pressure, and compact turbine design that won't disrupt water delivery. Additionally, turbines must avoid impacting water quality, as utility services prioritize stability and safety.

Regulatory challenges also exist, as complex permitting processes and fragmented oversight between water and energy sectors can delay or limit project approval. Permit acquisition for turbines within municipal systems can be costly and time-intensive, with few policy incentives to support energy generation by utilities. Addressing these barriers will require streamlined permitting, supportive renewable energy policies, and pathways for energy commercialization in water utilities.

The application of hidden hydropower technologies, whose design aims to exploit the untapped hydroelectric energy potential present in existing infrastructure not designed for energy generation (Hansen et al., 2023), is crucial in advancing the energy transition process. These technologies contribute to address challenges, increase efficiency, and facilitate the integration of renewable and sustainable energy sources into the power system. As these technologies progress, they significantly build a sustainable, clean, and advanced energy landscape, as well as empowering local communities to become active participants in the energy transition. In this context, the prosumer plays an important role, operating off-grid, with no reliance on the electricity grid. The primary trend in this field is the exploitation of hidden hydropower potential in existing hydraulic infrastructure and exploring new methods for incorporating other energy technologies into hydropower plants. This paper highlights the vital role of hidden hydropower technologies in shaping the future of hydropower systems and leading the way towards a sustainable energy revolution. The primary goal of all stakeholders in the energy transition process is the 'decarbonisation of power generation', which refers to the shared aim of promoting climate-friendly energy production.

In this context, decision-makers, engineers, and investors must conduct CAPEX (Capital Expenditure) and OPEX (Operations and maintenance costs) assessments to harness the full potential of hidden technologies within the hydropower sector, while ensuring economic feasibility. Both the integration of new renewable energy into the power system and the self-production of electricity from renewable sources for self-consumption yield immediate positive effects including the reduction of grid energy losses, the mitigation of congestion problems, and a decreasing need for the modernization of electrical infrastructures (Ciocia et al., 2021).

To the best of the authors' knowledge, discussing the role of available and newly-developed hidden hydropower technologies in the energy transition from an economic point of view represents today a

research gap. This manuscript stems from the presentations and discussions which took place during and after the workshop on "Water-Energy Nexus in the field of water-supply network" (19–20 October 2023, Vienna (Austria)), organized in the framework of the COST Action Pan-European Network for Sustainable Hydropower (PEN@Hydropower, CA21104). A guiding idea of this paper is to present hidden hydropower potential in different application fields, such as pressurized systems, hydropower storage and unpressurized systems, which have a very low environmental impact and can provide a significant contribution to the energy system. The objectives of this manuscript are to:

- i) analyze the role of the hidden technologies in the energy transition considering various application fields (Section 2 of the paper),
- ii) identify and present existing hidden hydropower technologies, as well as new ideas and recent developments (Section 3), and
- iii) assess the implementation of the described technologies from an economic and sustainability point of view (Section 4).

## 2. Hidden hydropower, an underexplored catalyst in the energy transition

Climate change, uncertainties in energy prices, rise in power demand and increasingly frequent flexibility requirements have boosted the global interest in new ways and techniques of producing, delivering and consuming energy, as well as in controlling energy consumption. With changed conditions in the electrical grid system, hydropower is more and more required to have a balancing role rather than primarily a production role. Besides the development of new projects, the exploitation of hidden and untapped hydropower potential represents a relevant aspect in the hydropower overall stake in the energy balance. The main difference between hidden and untapped hydropower is given by the physical layouts where these potentials are considered. In fact, hidden hydropower is exploited from the water systems primarily built for non-power purposes, such as irrigation circuits, water supply networks or cooling systems, whereas untapped hydropower considers refurbishment in already established hydropower plants through different kinds of improvements and upgrades (Hansen et al., 2023). Taking its characteristics into consideration, the authors assess the order of magnitude of hidden hydropower potential as smaller than the untapped potential of the existing hydropower plant.

The application of pico-hydropower energy systems, whose capacity up to 5 kW (IRENA, 2023) includes hidden hydropower technologies, is limited to the decentralized power generation systems (Powell et al., 2018) such as rural electrification (Lahimer et al., 2012; Williams and Simpson, 2009; Ohunakin et al., 2011) or as part of small agricultural communities (Doolla and Bhatti, 2006). Since the hidden hydropower potential is framed within the low-power energy sources, it is natural to use it as a stand-alone system for small independent communities and electrification in remote areas. In this context, the concept of energy communities or energy cooperatives can be developed in compliance with the goals of sustainability and locally-managed energy systems. On the other hand, hidden hydropower sources that are available in urban areas can be connected to the electrical grid to support the energy distribution.

One key notion regarding the integration of hidden hydropower sources in the grid-connected energy system is the concept of prosumer. According to Ford et al. (2016), prosumers have started to emerge during the past decade with the introduction of affordable renewable energy technologies (RET), such as solar photovoltaic (PV) panels. In this context, a high-level definition of an energy prosumer embraces the multifold nature of the role of a consumer who also produces, sells, trades, or stores energy. According to (Child et al., 2020), prosumers could self-generate up to 26 % of the electricity consumed by 2050. Energy prosumers can be an important driving force for achieving the target of 100 % renewable energy (RE100, 2018). The role of

pico-hydropower is recognized as part of prosumer energy systems (Brown et al., 2020) as well as playing also a role in addressing energy poverty and promoting sustainable development. According to IRENA (2023), small hydropower systems or mini-hydropower plants (< 1 MW) offer advantages in terms of secondary use, such as for irrigation, digitalisation or the direct utilization of the generated energy. This small-scale power system can also be used for implementing the Internet of Things (IoT). The aim of the IoT is to automatically collect relevant information from the real world, link it together, and make it available online. This approach is particularly beneficial for the digitalization of drinking water networks. In Tian et al. (2023), a relevant advantageous aspect emerges in the digitalization of drinking water networks. In particular, by data-driven monitoring of the water networks, valuable insights regarding water quality assessment, pressure levels and leakage detection can be collected. Addressing this need for information, also known as the information gap, is crucial for developing an intelligent water network that also optimally matches water demand with current and predicted consumption. The needed energy for the monitoring through sensors can be achieved through energy harvesters (see Section 3.1.2).

As a consequence of the substantial differences existing in the identified fields of application, hidden hydropower potentials can be divided into three main groups:

- Pressurized systems (freshwater distribution networks, cooling systems, irrigation systems, process engineering e.g. petroleum industry)
- Hidden hydro storage (pump storage for untapped water reservoirs, unused cavities)
- Open channel systems (irrigation system, wastewater, drainage channels, shiplocks)

Given the important differences in terms of power potential size and of energy content characteristics between these groups of power sources, the definition of the most suitable technologies to be implemented in view of an efficient power extraction is not straightforward. Therefore, a deeper understanding of the main characteristics of the above-mentioned hidden hydropower sources is of great importance.

### 2.1. Pressurized systems

Pressurized water distribution systems represent 2–3 % of global energy consumption mostly due to pumping (Mitrovic et al., 2021). Pressure regulation is the most common problem associated with the operation of pressurized water networks. Reduction of pressure and therefore leakages can be achieved by adding various regulation elements such as pump speed control, regulation tanks and automatic valves (Ramos et al., 2021). Pressure-reducing valves (PRVs) are indicated as the most widely used devices which control the pressure in water supply systems. The presence of pressure reduction devices in such installations reveals the existence of a hidden hydro potential which is currently not necessarily exploited. Therefore, electricity can be generated by exploiting excess pressure existing in water pipes without interrupting the primary function of such hydraulic infrastructure (McNabola et al., 2014).

Various studies proposed different solutions to improve the energy efficiency, and mainly focused their attention on the water distribution systems (e.g., Moreno et al., 2007; Crespo Chacón et al., 2019). For instance, Quaranta et al. (2022) investigated the use of micro-hydropower turbines, with installed capacity below 100 kW, in pressurized water distribution networks. The developed technology is environmentally friendly and has decreased civil work because of the existing infrastructure (Gómez-Llanos et al., 2018). However, energy savings can take place at other levels, such as the farm scale by exploiting the presence of excess pressure during irrigation. In remote rural areas, farms, which are disconnected from the electric grid

connection, rely on diesel generators for in situ energy production (Crespo Chacón et al., 2021). At the farm level, the sustainability of energy production can be improved by replacing diesel generators with micro hydropower (MHP) based on pumps as turbines (PATs), coupled to energy storage systems, or by complementing MHP with other renewable energies. For instance, Crespo Chacón et al. (2021) designed and tested a MHP pilot plant, which allowed saving 3000 L of diesel at the farm level from May to September, which offset 8.4 tCO<sub>2</sub> and saved over € 2250. Despite the challenging market fluctuations found in the excess pressure during the growing season, MHP based on PATs represents a viable solution that can meet the energy demands of farms for their irrigation systems. Overall, given the different purposes that pressurized systems are conceived for, the implementation of a potential recovery device may differ largely between the existing hydraulic systems.

In Spain, the energy consumption for irrigation spiked up to +657 % in the period 1950–2007 (Corominas, 2010). However, due to particularly strict regulations (no contamination allowed) and high security of supply that are applied to drinking water networks, the related investment costs for the extraction of power from the latter are substantially higher compared to what may be concerned for irrigation systems.

Additional solutions to take advantage of relevant excess pressure values can be identified in cooling and heating distribution networks which are often equipped with PRVs. In Sarbu et al. (2022), an investigation about the feasibility of installing micro hydro-turbines into the heat transmission network in Timisoara to recover hydraulic energy has been performed. Accordingly, 491 kW of electric power may be produced from the network's excess pressure during the heating season, which corresponds to the electrical energy of 1964 MWh/season. A further example of energy recovery in heating systems, includes implementing a turbine to exploit pressure difference between the supply and return pipes which is used to drive the circulation pump (Frederiksen et al., 2008; Wollerstrand et al., 2009). In cooling systems, surplus pressure generated when transporting water to coolers at higher levels can be harnessed for energy recovery. This surplus pressure, typically wasted, can be utilized by installing a hydraulic turbine on pressurized pipelines (Ma et al., 2017). Hidden energy sources exist within cooling towers (Zhou et al., 2015), where water contacts air to dissipate industrial waste heat. To harness renewable energy, an ultra-low specific speed Francis turbine was developed, installed within the cooling tower's inner platform. The turbine's shaft is coupled with the fan's shaft, allowing water circulating with surplus pressure to drive the turbine, which in turn spins the fan, reducing reliance on electric energy consumption.

The overpressure energy is widespread used in various industries, including oil refineries, natural gas treatment, desalination plants and the chemical industry. One of the energy-consuming processes in the petroleum industry is the hydrocracking process. During the hydrocracking process, the raw material passes through high and low-pressure devices in which PRVs are usually used to achieve the required pressure. By using a hydraulic machine instead of a reducing valve, the dissipated energy can be recovered instead of wasted (Goodarzvand-Chegini and Ghasemi Kafrudi, 2017). Authors found that nearly 436 kW can be achieved. In addition, Rossi et al. (2020) described the use of a hydraulic power recovery turbine in the context of an Italian oil refinery. Such turbines are used to replace a pressure-reducing valve in the H<sub>2</sub>S (hydrogen sulfide) removal process. The achieved economic saving is equal to approximately 260,000 €/year. Yearly electric energy recovery amounts to 2966 MWh with a maximum payback period of 9 years.

Another example of hidden hydropower application are desalination plants which use reverse osmosis to purify seawater from salt to produce clean water. For this, high pressure water passes through the membranes and is separated from the salt (Choulot, 2010). The desalination system cannot clean all seawater, because of the fouling of the membrane. Seawater treatment plants have recovery rates from 25 % to 45 %, while brackish water reverse osmosis plants have recovery rates as high as

90 % (Charcosset, 2009). The rest of the high-pressure concentrated brine that cannot pass through the reverse osmosis membrane could be recovered from the energetic point of view (Huang et al., 2020; Mirza, 2008; El-Emam and Dincer, 2014).

## 2.2. Hidden hydro storage

Pumped hydro energy storage (PHES) is commonly recognized as storage for energy produced by photovoltaic solar (PV) or wind energy (WE) (Rehman et al., 2015). Fast-paced increase of investments and developments of new PV and wind energy plants requires a lot of flexibility of the energy grid balancing systems, where pumped hydropower could have an important role in storing the excess of energy from PV and WE and using it for future electrical grid demand fluctuations (Blakers et al., 2021). PHES are very well suited in power systems given their fast-response for power regulation and their black start capability. In fusion with advanced computational models for optimization of water reservoirs operation, PHES could deliver additional energy surplus to strengthen its role in the energy system (Ahmadianfar et al., 2017; Samadi-Kouchehsaraee et al., 2018; Fang et al., 2021; Ahmadianfar et al., 2023) system.

Besides its balancing role in the energy system, PHES could also have a symbiotic relationship with other RES, where the integration of PHES and PV, for example, could have mutual technological benefits (IRENA, 2020a). Floating PV (FPV) that could be installed on the hidden hydropower reservoirs could decrease the water evaporation in the upper and lower basin of PHES, and the water could decrease PV panels temperature and mitigate thermal efficiency impact on PV panels (Cazzaniga et al., 2019). It is estimated that this technological integration could save up to 6 % of water losses for general FPV installation on water open surfaces (Kakoulaki et al., 2023). Along with water loss, there are transmission savings since the pumping power production is on the pumping near site. Interconnection between mentioned technologies are schematically displayed on Fig. 1.

Alternatively, in cases where the terrain does not allow for the utilization of traditional PHES, employing underground cavities might serve as a method to overcome the absence of upper/lower reservoirs (Martin, 2011). Nevertheless, the utilization of subterranean cavities as lower reservoirs in hydropower applications remains uncommon, and the technology associated with it has yet to progress beyond the research and development phase (Pickard, 2012; Morabito, 2022).

Some of the already built infrastructures in hydropower systems could also be used as hidden hydro storage, especially the hydropower plants that are used only seasonally (Münch-Alligné et al., 2021). Surge tanks (Richter et al., 2019), sediment settling basins (Münch-Alligné et al., 2021) and parts of the headrace tunnel are some of the usable underground structures that could be deployed in the off-season and used as storage for pumped hydropower potential. Various pre-existing infrastructures employed for different purposes have the potential to serve as reservoirs for water storage, which can be used during specific periods when energy demand is high. In alpine regions, there are water reservoirs equipped with pumps that currently work as water sources for producing snow at ski resorts. Throughout the year, this water source is solely utilized in winter and remains inoperative during warmer seasons. Leveraging the existing pumping system as a PAT solution could offer a cost-effective approach for energy storage with low CAPEX. In order to keep the investment costs as low as possible, a modular design of the PAT can be applied (see Section 3.2). The use of this hidden hydro storage potential could play a role in relation to the prosumer approach and help to build a decentralized power grid system, especially in mountainous areas. A combination with renewable energy sources in the local area can help to reduce the load on the power grid. Furthermore, decentralized electricity production shortens delivery routes and thus increases efficiency and reduces OPEX costs. This concept is therefore in line with the objectives for a decentralized supply system reported in the Green Deal (EC, 2019). From the wider point of view, the potential of

small hydropower is clearly recognizable. While plants in the 100–400 MW and 1–2 GW capacity range dominate, a large existing potential of water reservoirs could be tapped in the small hydropower sector with a capacity coverage of 5–40 MW. In view of the sharp increase in volatile renewable energies and the associated need for energy storage, this concept of decentralized storage offers great potential.

The majority of storage infrastructure suitable for exploitation as reservoirs for pumped hydropower relies on the difference in elevation between two basins. However, conveying this concept in urban areas or flatlands poses challenges. A couple of promising developments are underway towards implementation. These innovative concepts could be deployed in urban areas near coastlines or in flatlands. Both approaches involve the creation of flexible storage containers that are pressurized externally. Project Stensea<sup>1</sup> and Project OceanGrazer<sup>2</sup> have paved the way for future research towards exploitation of this hidden pressurized storage. Although the idea of this kind of potential exploitation was born earlier (Slocum et al., 2013), the contribution of those two projects brought the technology closer to its exploitation form. The potential of this technology is enormous (Puchta et al., 2017) and it is estimated more than 800,000 GWh storage capacity worldwide. Since the combination of this technology with wind energy and wave energy is natural as a source for pumping energy (Gao et al., 2024), its symbiotic relationship shows its benefits in joined infrastructural development. Besides benefits, the technological difference between i.e. wind power plants and underwater pressurized water storage could be an obstacle in finding suitable locations for the installation of these technologies in narrow geographical areas (Hahn et al., 2017). Offshore wind turbines are usually installed in shallow waters near the coast, and underwater pressurized water storage requires depths up to 800 m to be financially feasible. A similar technique could be applied on-shore, but instead of using hydrostatic pressure, lifting the weight of soil could be used as a pressure induction mechanism (Olsen et al., 2015). This underground pumped hydro storage (UPHS) concept relies on a double-membrane storage cavity which is buried underground. Preliminary results analysis presented by Olsen et al. (2015) show a financially feasible technology with a promising future development.

## 2.3. Unpressurized systems, open channel

The functioning of wastewater treatment plants (WWTPs) determines 2–3 % of global energy consumption (Mitrovic et al., 2021). WWTPs are facilities employed to reduce the potential environmental impact of wastewater discharges into the environment (Molinós-Senante and Maziotis, 2022). Several assessments of the recovery potential of such installations are being conducted (Power et al., 2014; Mérida García et al., 2021; Baran, 2021), as well as investigations characterizing the potential for implication of renewable hydro-energy sources in the facilities of WWTPs (Ho et al., 2014). The high amount (about 360 km<sup>3</sup>/year) of municipal wastewater shows the great potential for the use of wastewater flow to obtain hydropower (Tomczyk et al., 2023). Since the discharge of these facilities is generally considered as constant, the need for additional reservoirs can be avoided (Purece and Panaitescu, 2023). In this regard, Bousquet et al. (2017) provides a detailed inventory concerning existing hydropower plants (HPPs) installed in waterways systems worldwide. This overview covers HPP's installed power values going from tens of kW to a maximum power of 4.5 MW, and highlights the important versatility of HPP technologies to fit a wide range of discharge and head. Regarding unexploited existing potential, Mérida García et al. (2021) concentrates the research to Spain and identifies a power recovery potential between 3.3 and 3.5 MW excluding WWTP discharge licenses unable to provide at least 2 kW. In Abbas et al. (2019) and Sinagra et al. (2021), two methodologies to determine the

<sup>1</sup> <https://www.iee.fraunhofer.de/en/topics/stensea.html>

<sup>2</sup> <https://oceangrazer.com/>

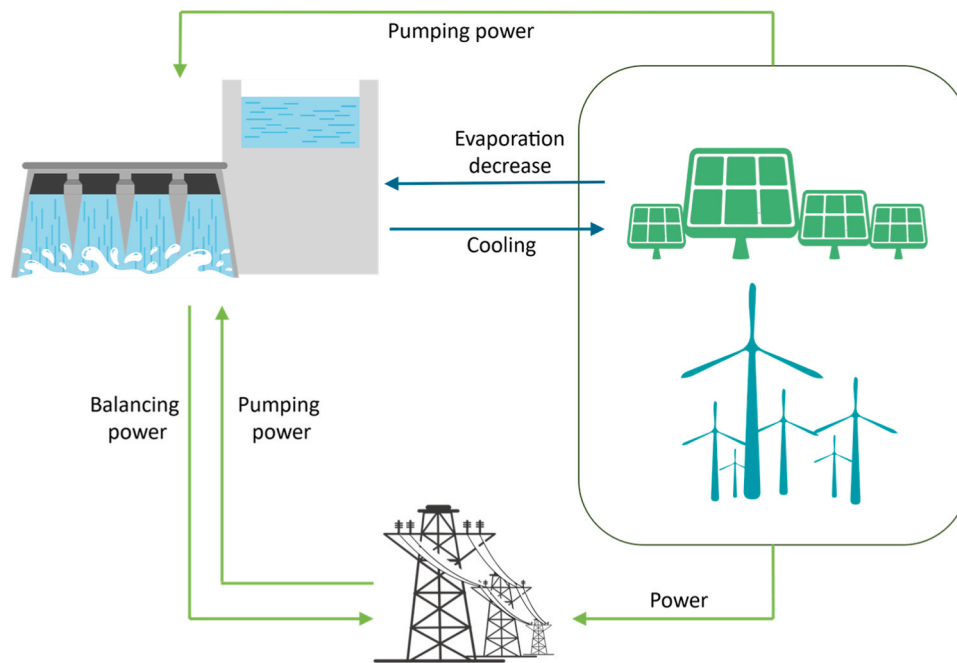


Fig. 1. Symbiotic relationship between hydropower and PV solar plants.

potential energy estimation in real cases study of WWTPs, respectively in USA and in Italy, and the consequent most suitable low-head turbine characteristics to be coupled to the WWTP are illustrated.

There are two possible areas of hydropower generation at WWTPs, at the inlet and at the outflow of the facilities. A turbine setting before the WWTP can lead to difficulties in the normal operation due to the untreated wastewater quality and clogging of the runner (Punys and Jurevičius, 2022). Thus the need of a forebay equipped with a thin trash rack and a rack cleaner is imposed. In addition, the hydraulic turbine should be placed as close as possible to the WWTP to maximize the head (Choulot et al., 2012). In the case of pollution of the water it is more viable and effective to install the machinery at the outflows. The discharge of treated water is usually released into natural systems. This happens via channels using just gravitational power to transport the water (Purece et al., 2023). To maximize the head (in case when the HPP is set after the WWTP), the turbine should be situated close to the restitution (Choulot et al., 2012). Installing a proper turbine combined with high discharges and the difference in head (up to 10 m) results in relatively high potential for hidden hydropower applications (Purece and Panaitescu, 2023). An example is provided by Gude (2015), for the case of a WWTP in Vienna, Austria, featuring a 5 m elevation drop between the headworks and the Danube River. The vertical axis turbine generates 2.6 % of the electricity required for the operation of the treatment plant. Another successful example of the use of wastewater energy is the treatment plants of Clark County, USA. The 16 MW hydroelectric generating station produces more than 85 million kWh per year, while the pumping demand was 4 million kWh. The WWTP has an elevation drop of 120 m to the effluent (Maktabifard et al., 2018). In the UK, an Archimedes screw turbine has been installed to recover energy from the WWTP, where the total power provided by two turbines is 180 kW, equivalent to a €160,000 saving in annual electricity costs (McNabola et al., 2014).

Shiplocks also feature hidden hydropower potential. Basic shiplock contraction uses a fixed chamber with two pipeline systems and various valves. The process of filling and emptying the fixed chamber depends on the direction of each ship motion. The repeatedly changing head in the fixed chamber offers the possibility of installing turbines in the river locks pipeline systems (Zhu et al., 2023). In the case of existing locks, the process of installing new turbines is nearly impossible without major

civil engineering modifications, leading to significantly increased initial cost (Zhang et al., 2018). Moreover, the very low available hydraulic heads and repeatedly changing discharges induce important challenges to be considered, raising relevant issues regarding the economical reward and the technical feasibility in realizing such setup. However, due to the number of shiplocks currently installed on the rivers and the incoming duty of self-sufficiency, hydropower potential of these facilities might come into consideration. In (Zhang et al., 2018), an ongoing project started in 2018 to be applied to shiplock processes that aims to develop a hydropower generator designed to operate in a 30–60 kW range is illustrated.

### 3. Hidden hydropower technologies

The quantity of unexploited energy of hydropower around the world that could justify the investment is 5.27 PWh annually, according to Xu et al. (2023). Although Europe has a large unused and technically feasible hydro potential of 1.28 PWh annually (World Atlas of Hydropower and Dams, 2022), less than 0.3 PWh annually is financially profitable (Xu et al., 2023). The extraction of hidden hydropower in infrastructures not specifically built for hydropower generation can reasonably be considered as upper-bounded to 500 kW (Hansen et al., 2023; McNabola et al., 2022), i.e. the size recognized as the upper bound in the micro-hydropower definition (IRENA, 2023). However, besides the financial profitability of the identified hidden hydropower potential, different social, ecological and legal factors may represent strong constraints towards the potential exploitation.

One of the major advantages of the hidden hydro implementation on the available non-power hydraulic infrastructure is that it does not have any significant impact on the environment (Hansen et al., 2021). On the other hand, low energy capacity could be limitational for the implementation of hidden hydro technologies as a competitive player in the energy system. In this regard, the existence of a water flux featuring discharge and head values ensuring a power flux in the mentioned power range is of vital importance. Given this constraint, the existing sites and infrastructures to be considered as potentially relevant must be identified and classified, and their power range accurately evaluated.

The exploitation of the hidden hydro potentials can be conceived by using different kinds of available and earlier-developed technologies,

such as pumps-as-turbines (PAT), hydrokinetic turbines, run-of-river turbines, counter-rotating turbines, and low-head turbines. The technology that is used for the proper energy transfer differs according to the hydraulic potential and available manipulation space of each location. In contrast to the common hydro technologies that are already in use, new technologies are currently being developed and implemented. As stated above, there are several promising types of technologies. This Section provides an overview of the most relevant technologies to be coupled to the fields of application mentioned in Section 2. Both existing technologies (i.e. present on the market) and new projects (i.e. still in their development phase) are illustrated and discussed.

### 3.1. Technology identification: Pressurized systems

To effectively identify the most suitable technology to be implemented in pressurized systems, an evaluation of the available hydraulic power potential must be performed. The hydraulic power  $P_h$  is defined as follows:

$$P_h = \rho Q g H \quad (1)$$

with  $\rho$  the density of water,  $Q$  the discharge in  $\text{m}^3/\text{s}$ ,  $g$  the gravity acceleration and  $H$  the available head in m which is given by the static and dynamic terms of the pressure in the hydraulic circuit. In case of energy conversion in pressurized systems, classic hydraulic turbomachinery technologies take into account the weight of head and discharge in the potential energy content of the water flux through the specific speed defined as:

$$v = 2^{1/4} \pi^{1/2} n Q^{1/2} (gH)^{-3/4} \quad (2)$$

with  $n$  the rotating speed of the machine in  $\text{s}^{-1}$ . Lower values, typically in ranges up to 0.15, are typical for impulse turbines, whereas reaction turbines feature higher specific speeds: radial turbines present values roughly in [0.15; 0.6] while axial turbines are usually designed for ranges  $v = [0.6; 2]$ . Therefore, the identification of the most suitable device to be implemented in pressurized systems strongly relies on the evaluation of head and discharge of the power potential of interest.

#### 3.1.1. Existing technologies

Energy recovery in pressurized systems is becoming more common. Pumps-As-Turbines (PAT) (Fig. 2.) are already used for efficient recovery of energy in pressurized water distribution networks (Pérez-Sánchez et al., 2017). Low cost, immediate availability and large operation ranges make these machines a good option as energy recovery devices. However, in the case of efficiency there is a difference between pump and turbine mode. The efficiency of PAT in turbine mode at the best efficiency point (BEP) is usually between 65 % and 75 %, which is by 10–20 % less than in the case of normal turbines (Kramer et al., 2018). In the case of the BEP the question of regulation of discharge and head

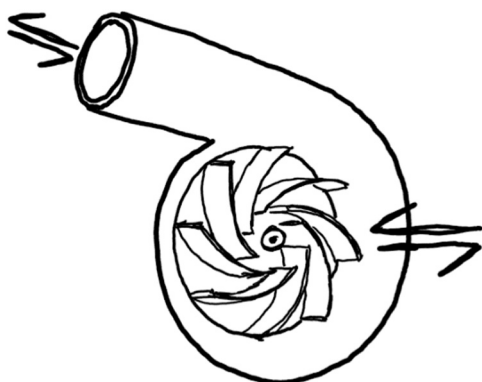


Fig. 2. Schematic view of PAT.

arises. There are two main types of regulation in terms of PAT. Bypass with regulation valves or frequency converter. A huge advantage of the bypass method comes in the form of the constant rotational speed of the PAT's shaft (Pérez-Sánchez et al., 2017). However, it requires quite a lot of assembly space which may not be present in certain locations. In addition to that, a certain number of hydraulic losses come with the usage of the bypass method. On the contrary, using a frequency converter provides a much more compact but costly solution. In both cases mentioned above, CAPEX and OPEX assessments are crucial for the final decision. Later on, a concept of a modular pump turbine is presented that utilizes the advantages of the classic reversible pump turbine (PAT) and eliminates the major disadvantages through modularity and state-of-the-art technology such as speed control. The additional modularity allows a design ready for series production and thus an improvement in CAPEX and OPEX.

Inline vertical axis water turbines are often used in pipeline systems. This type of turbine may use the pipe wall as a turbine body. Yao et al. (2022) added to the turbine the bell-mouth guide block at both sides of the impeller (Fig. 3). Such turbines may be used in pipes with bidirectional water flow. The impeller has spherical blades. The middle part of the blades is hollow. During the experimental studies, the water turbine produced an output power of 17–88 W at a water flow velocity of 1.5–3.0 m/s.

In axial-expansion turbines (AXENT) the flow is parallel to the axis of rotation as opposed to cross-flow turbines (Dave and Franck, 2021). An axial turbine can have one or more stages consisting of a stator and a rotor (Agromayor and Nord, 2019).

Their design is constantly being improved and new methods of tubular turbine design are being developed. Authors (Vivas et al., 2021) create a dimensionless design chart that allows the fast design of families of tailored pico-hydraulic turbines. The methodology for designing the stator and rotor blades for an axial expansion turbine is shown in the article (Nemet et al., 2019).

Kaplan turbines can also be used for in-pipe applications (in-line Francis turbines). However, such turbines need a bypass loop. The bulb-turbine is a more compacted axial flow type turbine, essentially a Kaplan turbine variation. In such turbine wicket gate, and the runner of the turbine are housed together in a large bulb. This design allows them to be placed in water supply pipelines (Sari et al., 2018; Chaulagain et al., 2023).

The main advantage of axial-expansion turbines is that they do not generate a significant pressure surge in the event of a sudden stop due to power failure, unlike other turbines.

#### 3.1.2. New ideas and developments

Here we investigate these two ideas:

- H-HOPE Harvester
- Duo-Turbo concept

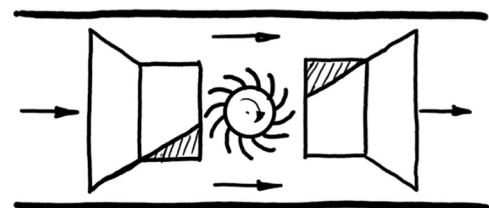


Fig. 3. Schematic of water flow in the inline vertical axis water turbine (adapted from Yao et al., 2022).

**Ad a)** In a novel EU project called H-Hope<sup>3</sup> (Hidden-Hydro Oscillating Power for Europe), a new technology is being developed to extract and harvest energy from existing water supply systems for non-hydropower hydraulic systems. To extract electric power the principle of piezoelectricity is combined with the Karman vortex street (Fig. 4). Piezoelectric mats produce energy when they get bend. To bend these mats, they are bonded on hydrofoils which are directed into the flow of different pressurized applications. The design of these wings is executed in a manner that the release frequency of the Karman vortex exactly matches the natural frequency of the wing. This results in maximum deflection, which in turn increases the energy transfer to the piezo mat. The piezo patches absorb the energy generated by the resonant vibration and conducts the energy to the outside. A typical installation application could be a piping system for drinking water. As the supply from the drinking water network must always be guaranteed, energy generation is of secondary interest. This also limits the maximum pressure drop and therefore the maximum energy yield. To ensure that profitability (CAPEX and OPEX) is nevertheless maintained, the energy generated can be used directly, even if it is only in the lower watt range per system. For example, for the Internet of things (IoT), the energy generated can be used to supply additional installed monitoring sensors and thus to expand the SCADA system in the drinking water supply and foster an intelligent water network. By additionally monitoring the drinking water network, water losses can be identified and removed. This technology could also be installed in remote locations without a direct power supply and perform autonomous data collection. Further utilisation of data in IoT and a clever approach to AI-based analysis can drive the development of cost-effective, automated (or even autonomous) digital services. This brings various benefits, such as reducing energy/water consumption and early detection of maintenance or replacement work in the water infrastructures.

**Ad b)** Part of the small hydropower potential in Switzerland exists in drinking water networks of alpine areas, but remains untapped due to lack of profitable solutions. HES-SO Valais-Wallis and EPFL-LMH have initiated the DuoTurbo<sup>4</sup> project in 2019 which is considered to be the first implementation of a counter-rotating microturbine in a real drinking water installation. The prototype was embedded at a drinking water network in Savièse, VS Switzerland, which experiences large variations in both head and flow rate. The maximum power output is 6,5 kW, while the peak efficiency is 59 % at a hydraulic head of 75 m (Biner et al., 2021).

According to Andolfatto et al. (2015), water is collected and stored in a reservoir near the spring at a higher elevation ( $Z_s$ ) than the water drinking network elevation ( $Z_c$ ) where the pressure is constrained to  $p_{max}$  in order to prevent equipment damage. PRVs are often used for pressure regulation, instead the dissipated energy is recovered with a counter rotating turbine. Thus, the turbine partially replaces the

function of existing pressure release valves that protect the water system from overpressure. The specific energy of water  $Y$  extracted from the flow equals the difference between the specific energies between the headwater section and tailwater section. Neglecting pipe hydraulic losses, the hydraulic power estimated is

$$P_h = QY = Q [(Z_s - Z_c) - p_{max}/\rho] \quad (3)$$

The DuoTurbo microturbine is an axial flow turbine with two serial counter-rotating runners per stage. Connecting into stages allows utilizing excess hydraulic power in order to increase generating capacity. Each runner is featured with a wet permanent magnet rim generator with independent speed control. The space between the two runners is vaneless which contributes to simplifying the design, while the counter-rotating runners attribute to high specific powers and efficiency. High operational flexibility is achieved by the speed ratio between the two runners which allows adapting to off-design conditions. The safety in turbine operation without interference with the drinking water network is ensured by two PRVs. The low investment costs due to simple modular in-line installation allow economical generation of 5–25 kW power.

Münch-Alligné et al. (2013) showed that changing the rotational speeds ratio affects the turbine efficiency curve. Double rotational speed regulation provides flexibility in operation. The total output mechanical power is a sum of each runner's mechanical power calculated as a product of the torque  $M$  and angular velocity, i.e.

$$P_m = M_1 2\pi n_1 / 60 + M_2 2\pi n_2 / 60 \quad (4)$$

Hence the efficiency is calculated as  $\eta = P_m / P_h$ . This allows the possibility to find the optimal set of rotational speeds ( $n_1$  and  $n_2$ ) for a certain operating point.

At the pilot site on a drinking water network in the Swiss Alps, the reservoir is around 190 m higher than the relief valve which ensures constant tailwater pressure of 6,5 bar. The specific energy that can be recovered is estimated as a function of the discharge. It was concluded that the limited discharge is a constraint of higher efficiency, but can be overcome by increasing the range of rotational speed (Vagnoni et al., 2015).

### 3.2. Technology identification: Hydro storage

The machines used for pumped storage differ in their design. Classic ternary machine sets use a motor generator, a turbine, and a pump. This concept has many advantages in terms of fast changeover times but is associated with high investment costs due to two machine sets and a large installation space, making it unsuitable for use in the lower kW range. Here, the focus should be on smaller and more cost-effective machine sets, which is achieved with the combination of a pump and turbine in a reversible pump-turbine. While the efficiency of a reversible machine set decreases, the lower investment costs result in faster amortization, making investors more willing to invest. Studies such as one published by Morabito et al. (2020) prove the ongoing process to assess the feasibility of these possible hidden hydro storage technologies. The study shows that a suitable choice of turbomachinery is required and generally leans towards pump-turbine units. Having a separate pump and turbine would increase costs, complexity, and excavation costs. The main drawback is the complexity of starting the unit in pump mode, requiring a dedicated system (Auxiliary turbine, Frequency converter).

#### 3.2.1. Existing technologies

There is a large overlap or correspondence with the technologies for pressurized systems of the chapter before. However, a pump is always required for storage. Large machine sets are not affordable for small hydropower plants. The PAT, as already mentioned in 3.1.1, provides a remedy here. It can be produced in large quantities and therefore offered at a favorable price. The application range of small pump turbines is

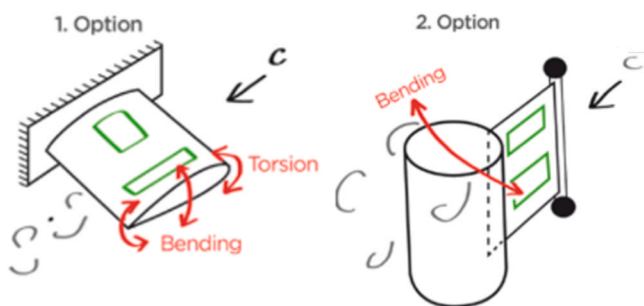


Fig. 4. Schematic of oscillators with piezopatches.

<sup>3</sup> <https://h-hope.eu/>

<sup>4</sup> <https://www.hevs.ch/en/projects/duo-turbo-8924>

limited by the low head that can be achieved. If higher heads (>100 m) are required, the system can be interconnected with several pumping stages.

### 3.2.2. New ideas and developments

A modular pump turbine makes it possible to generate electricity with the same machine design by adding or removing another stage to the basic pumping rotor, offering flexible storage for volatile electrical energy from 0.5 to 15 MW. This flexibility allows for the utilization of water from reservoirs at different heights with varying pressure levels. In addition, by using several machines in parallel sets, a big variety of discharge can be achieved. Furthermore, the range can be increased by variety on the electrical side. The use of a frequency converter enables a variable speed change, which in turn enables a variable flow rate. The electrical components are already ready to use on the market. Different capacities of the reservoirs and the associated power yield can be better managed by this modular design, ensuring system efficiency of 70–80 %. An already existing model (Doujak et al., 2012) is already in development (Fig. 5.), offering a short reaction time of just a few minutes between electricity storage and supply.

### 3.3. Technology identification: Unpressurized system, open channel

Similarly to the pressurized systems, even in the case of the open channel systems an evaluation of the available hydraulic power must be performed. In contrast to the pressurized systems, the velocity of the flow plays a significant role in the evaluation of the power. The hydraulic power for this case is defined as follows:

$$P_{hu} = KA\rho v^3/2 \quad (5)$$

where  $\rho$  is the density of the water,  $A$  the area of the turbine,  $v$  velocity of the flow and  $K$  the power coefficient. This coefficient is a measure of the fluid dynamic efficiency of the turbine, and it is different for each type. It is important to note that in the case of energy conversion via oscillating systems, the hydraulic power is evaluated differently:

$$P_{ho} = \pi DLv^2 C_L y_m f \sin \phi / 2 \quad (6)$$

where  $D$  is the characteristic dimension of the oscillating body,  $L$  its length,  $C_L$  the lift coefficient,  $y_m$  the maximum amplitude and  $f$  the frequency of the oscillation.

#### 3.3.1. Existing technologies

In the case of open channel flows with renewable energy potential,

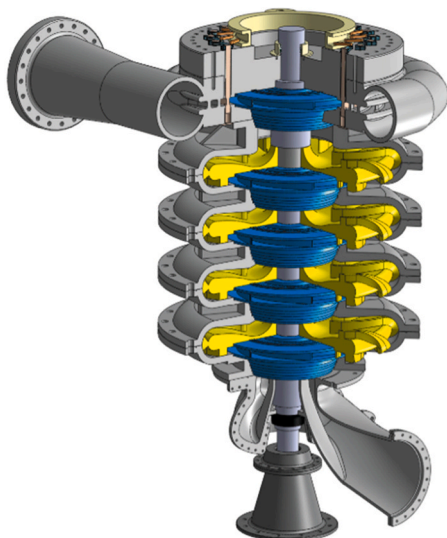


Fig. 5. Cross-section of modular pump turbine (Doujak et al., 2012).

so-called kinetic turbines came to the hydro-energy spotlight a few years ago. There are several types of turbines using this specific type of energy transfer. In research presented by Laws and Epps (2016) an outlook of those systems (and more) is provided. These kinetic turbine systems can also be used as a hydroelectric power plant located within the riverbed and operate without water storage. Purece and Punaitescu (2023) presented an overview on how channel walls, small footbridges, and road bridges built over canals can be used for installing turbines, is provided. To avoid the phenomenon of foreign matter in the flow, propeller-type hollow micro-hydraulic turbines are currently under development (Uchiyama et al., 2018). One cheap solution is the Savonius turbine. The basic shape of the Savonius rotor is an 'S' type, having a small overlap between two semi-circular blades. This technical solution is advisable to apply for rivers with a flow velocity of 0.5 m/s and above (Kumar and Saini, 2016). Despite numerous design improvements (Jeon et al., 2015; Mosbahi et al., 2018) this turbine is not widely used due to low efficiency. Countries with snowy winters develop and use turbines considering the passage of snow masses through the rotor (Satou et al., 2023).

It is possible to approach the problem of open channel flows from a different perspective. Similarly to the pressurized systems, it is possible to use vortex induced vibrations (the effect of the Karman vortex street) to generate a certain amount of electricity. For over two decades there have been several studies with a main goal of creating a self-maintainable device capable of transforming the energy of ocean/river currents. The most noticeable device is the device invented and patented at University of Michigan called VIVACE (Bernitsas, and Raghavan, 2009). This device consists of an oscillating cylinder mounted on a linear generator with an adjustable stiffness via a so-called virtual damper (Lee et al., 2011). For its correct function it is necessary to acquire resonance, lock-in mode and the highest possible amplitudes. Lock-in mode is crucial for the device to operate in a larger interval of flow velocities. To enhance the energy conversion rate, strips with certain roughness are applied on the surface of the oscillating cylinder. This provides a passive turbulence control (PTC) for the separation point and type of boundary layer (Chang and Bernitsas, 2011). It is important to note that the power harnessed from the flowing water via these energy harvesters is in the range of a single watts.

#### 3.3.2. New ideas and developments

According to the previous results from studies about VIVACE devices with a single cylinder, several studies about multiple oscillating cylindrical and non-cylindrical converters have emerged in the past few years (Xu et al., 2018). The conditions of a proper function of the converter are similar to the single cylinder devices, although significantly more difficult to achieve. Main challenge of present studies and experiments is to find correlation between mass/damping ratios, frequency and position/spacing of the oscillating bodies. Proper combination of the correlations could lead to synergy between the motion of the converters thereby amplifying the energy transition ratio (Xu et al., 2018). Most recent studies dive into the effect of free surface of a water flow. The distance between the converter and the free surface has a direct effect on the type of the vortices in the wake of the oscillating body as well as on the response amplitudes/frequencies and harnessed power/efficiency (Xu et al., 2020).

As stated in 3.1.2, EU project H-HOPE patronizes a development of energy harvesting technology to extract energy from existing water supplies. On the contrary to pressurized systems, in the case of the open channels an oscillating cylinder of variable diameter hooked on the nodding device is used, as shown in Fig. 6. This device is then connected to a linear electromagnetic generator to convert the oscillating movement to electricity. Due to the need of ensuring the lock-in mode to occur, several prototypes with different variations of damping/stiffness/mass-ratio coefficients and types of motion conversion are yet to be developed. Similarly to the energy harvester developed for the pressurized systems, the range of the power is very limited and particularly low (up to single watts). Thus, ensuring that it can be used to supply

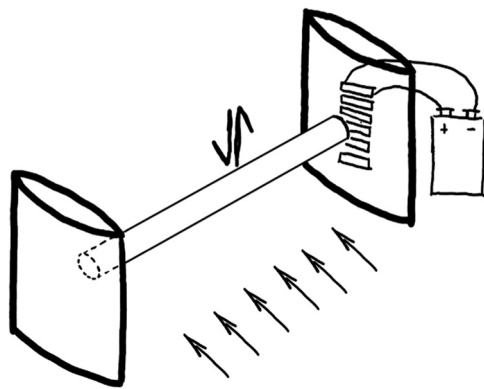


Fig. 6. Schematic of oscillating cilinder for open channel.

electricity to pressure or other types of sensors without the need for power cables or batteries.

### 3.4. Summary

A systematic overview of the Section 2. and 3. with the mutual interactions between hidden hydropower infrastructure and technologies is displayed in Fig. 7.

## 4. Economic impact of technologies and application

In this section, the economic and sustainability considerations on hidden hydro technologies are investigated, and key factors that influence their economic, sustainability and viability are examined.

The table below organizes various economic ideas according to their potential/application area, the technologies involved, and the expected power output. Based on the power output, different economic or sustainability approaches can be discussed for each category/variant.

### 4.1. Integration with electricity grid and off-grid solutions

Integrating hidden hydropower technologies with electricity grid is possible by building new transmission lines. However, connecting new hydropower systems to existing electrical grids can be complicated due to poor available infrastructure and accessibility leading to expensive and time-consuming process of grid upgrade. The need for extensive grid expansion can be reduced by implementing decentralized mini-grid solutions. A mini grid is a localised power generation and distribution network usually developed as a cost-effective approach to provide power for remote and rural communities that do not have access to a national grid (Uamusse et al., 2019). These systems can be designed to minimize the need for large-scale construction or land use. There are already developed mini grid solutions which need less construction work and provide straightforward site installation because of the full

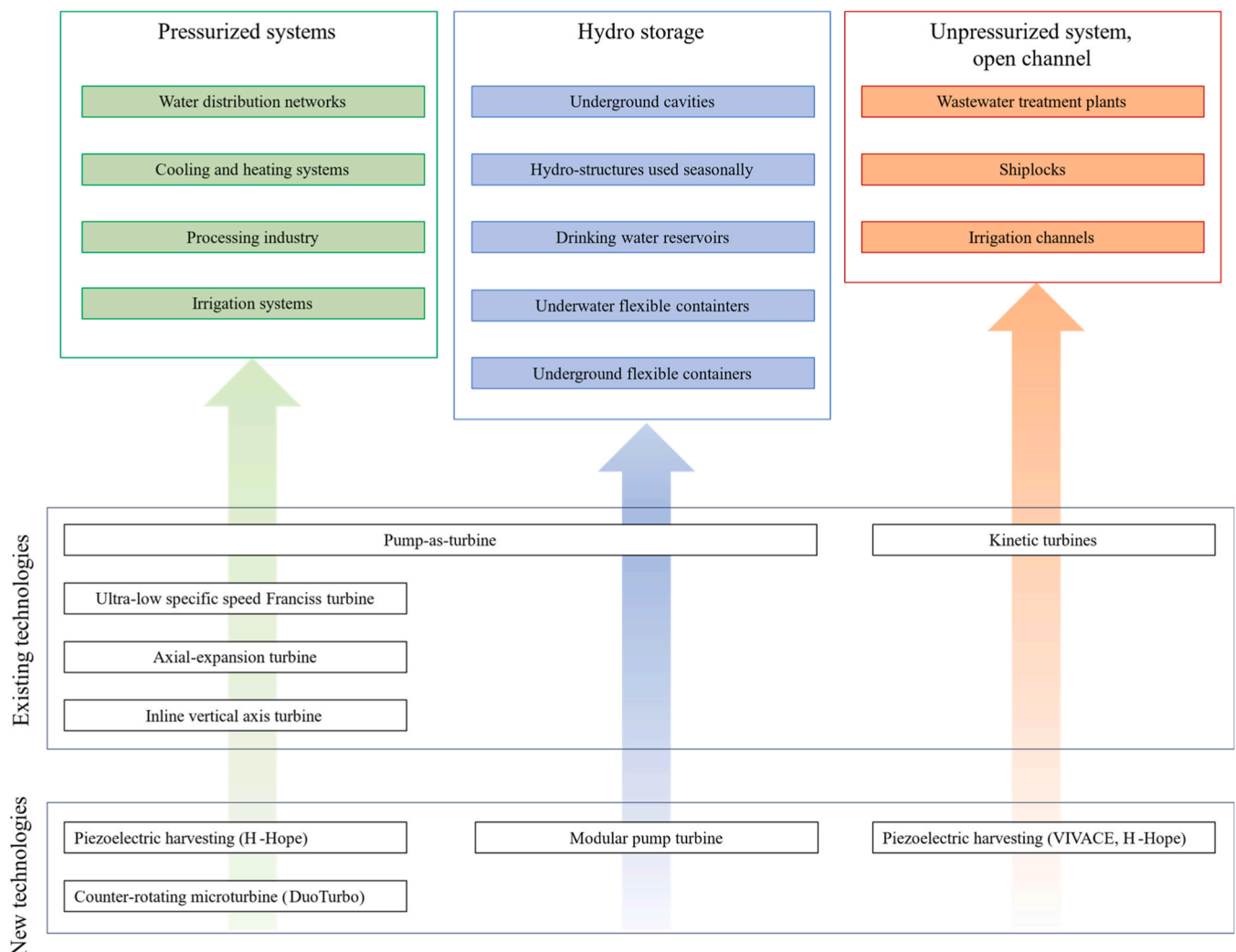


Fig. 7. Interconnection between different types of hidden hydropower infrastructure and technologies.

assembly, simpler operation and lower maintenance requirements. Mini grids can be later connected to a central grid by developing smart-grid technologies that provide real-time monitoring and grid conditions management in order to avoid problems with grid instability such as voltage fluctuations and frequency imbalances (IRENA, 2020b).

In order to ensure scalability, new design methodologies for hidden hydropower can be developed and applied. For instance, modular units are easily deployed and scaled based on local conditions, i.e., different demands and infrastructure limitations (Azimov and Avezova, 2022).

Considering energy distribution and grid connectivity, regulatory frameworks should be updated to support distributed energy resources and decentralized energy generation by simplifying permitting processes, offering clear guidelines for connecting to the grid, providing priority grid access and incorporating financial incentives (IRENA, 2020b) to encourage investments in hidden hydropower.

According to IRENA (2023), there is an installed off-grid capacity of 1.8 gigawatts (GW) globally, referring to decentralized or standalone systems that are not connected to the main electricity grid. In this context, this can include various renewable energy sources and technologies designed to provide electricity to remote or isolated areas where grid connection may be challenging or uneconomical.

The use of off-grid solutions in pressurized water distribution systems enables access to clean and reliable water in areas where conventional infrastructure is impractical or unavailable. Ortega-Arriaga et al. (2021) in their study reveal a significant cost disparity between off-grid and grid electricity access, with off-grid systems ranging from approximately \$0.2 to \$1.4/kWh compared to grid access ranging from below \$0.1/kWh to over \$8/kWh. This suggests that in many cases, off-grid access may be the more economical choice (Ortega-Arriaga et al., 2021). As it can be seen from the table, in the Variant A where Power output is between several kW and lower MW range, grid-connected horizontal-axis hydrokinetic turbines are eco-friendly power sources for electrical energy supply to households near middle-to-high discharge rivers, while providing an opportunity to sell the energy surplus. When implementing hidden technologies like pressurized systems, Pump storage Plants (PSP), and hydrokinetic turbines for electricity generation with the intention of selling electricity to the grid, it's important to consider the economic viability of the investment by applying principles similar to those used in conventional power supply, where factors such as market prices, technology costs, and return on investment (ROI) have to be taken into account.

Assessing the financial viability of renewable energy systems (RES) requires a thorough analysis of several components, including resource availability, initial investment costs, and local electricity prices including policy decisions. Regions rich in renewable resources like solar, wind, and hydropower tend to have lower production costs, while off-grid systems often face higher upfront and maintenance expenses, making them more appealing in areas with high grid electricity prices. Technological advancements significantly influence investment decisions, with photovoltaic technology being the most reliable option despite uncertainties, while wind and wave technologies are more affected by climate and technology risks. Combining solar-PV panels and wind turbines enhances energy capture and reliability, particularly in remote areas where grid expansion is costly. Additionally, energy storage systems are essential in these hybrid setups to manage power generation intermittency and support critical functions such as frequency regulation and voltage stability (Koochi-Fayegh and Rosen, 2020).

#### 4.2. Integration with prosumer dynamics and sustainable energy solutions

Kengne Signe et al. (2017) show that micro hydroelectric plants are widely acknowledged for their potential to provide energy solutions that are environmentally sustainable, cost-effective, and reliable for rural communities in developing countries. Once installed, these systems have low operational and maintenance costs, making electricity more affordable for local residents compared to other energy sources such as

diesel generators or grid connections. The development and operation of micro hydroelectric plants create employment opportunities for local communities, providing jobs and income for residents in rural areas, which can be obtained from construction and installation to operation and maintenance. Different authors have presented different approaches to estimate the cost of Pelton, Francis, or Kaplan turbines (PAT) and generators.

In remote or rural areas where access to centralized electricity grids is limited, micro-scale hydropower systems can provide off-grid energy solutions by powering small communities, farms, or individual households, reducing reliance on fossil fuels and diesel generators and improving energy access and reliability. In this context the prosumer concept is playing a pivotal role. According to the IEA recommendations by 2030 (IEA, 2023), 60 % of new capacity (equivalent to 571 TWh) for rural areas worldwide should be supplied by renewables. By the same year, 70 % of rural connections will be off-grid (IEA, 2023) by providing insight into the role of energy access for the environmental sustainability of developing rural areas. These hidden technologies are considered for both home- and small-scale community systems. Generally, these technologies include solar photovoltaics (PV), wind turbines, diesel generators, and batteries. In the Prosumer concept applied to hydroelectricity, technologies like PATs, counter rotating devices, axial inline turbines, hydrokinetic turbines, and energy harvesters play significant roles in enabling decentralized and sustainable energy production.

Ramos et al. (2009) proposed that the cost of a PAT varies between 200 and 400€/kW for nominal power lower than 40 kW. On the other hand, Carravetta et al. (2013) proposed different facts, estimating the cost of the PAT and generator to be 230€/kW and 115€/kW, respectively. It can be concluded that, from an economic perspective, pressurized systems offer the potential for improved efficiency, productivity, and resource utilization in industrial processes. Moreover, for a specific rated power, the estimation of costs may vary depending on the head and discharge available to the installation. In fact, according to Paish (2002), high head hydro generally provides the most cost-effective projects, since the equipment costs for installations featuring high discharge and low head are usually more relevant compared to ones estimated for high head installations.

In this context, it is essential to consider factors such as safety, reliability, environmental impact, and lifecycle costs when evaluating the economic feasibility and benefits of implementing pressurized systems. To assess the economic feasibility of employing PAT in Micro Hydro Power (MHP) projects, several financial metrics including the net present value (NPV), payback periods (PBP), and the cost of energy (Ec) could be analyzed. This evaluation should incorporate data such as initial investment costs (IIC), maintenance costs (Mc), and feed-in tariffs. According to Laghari et al. (2013), the total cost of micro hydro-power plant consists of four main parts. The most expensive is the construction part which takes up to 40 % of the total system cost followed by electrical and mechanical equipment cost (turbine generator set) which is 30 % of the project cost. The control equipment and management cost consist of 22 % and 8 % respectively.

In water supply networks, the electricity generated from renewable sources like solar panels installed along the network could be utilized to power UV disinfection systems for drinking water, thus promoting sustainability by reducing reliance on external energy sources. Similarly, at WWT plants, surplus electricity generated by prosumers could be employed to power pumps or other equipment, contributing to energy self-sufficiency and potentially reducing operational costs.

In the framework of sustainable energy as well as in facilitating the energy transition towards a low-carbon energy system, prosumers can create peer-to-peer microgrids or communities with established guidelines promoting the sharing of local renewable resources. The utilization of devices powered by advanced communication and information technology, has proven to be effective, safe, and holds great promise for the future of sustainability of energy (Hu and Chuang, 2023). In light of

this, Peer-to-peer (P2P) trading has emerged as an attractive model for prosumers looking to participate in the energy market actively, facilitating the exchange of excess energy among prosumers, creating mutually beneficial outcomes for both sellers and buyers. Given this context, the adoption of feed-in-tariff (FiT) has become widespread, enabling prosumers for their active role in the trading of energy markets.

Prosumers, who generate their own electricity (e.g., via solar panels), can sell excess energy directly to other consumers or prosumers being more profitable than selling it back to the grid at wholesale rates. P2P trading enables prosumers to become more self-sufficient by allowing them to manage their energy production and consumption more effectively.

P2P trading can alleviate the strain on the grid during peak demand periods by enabling localized energy exchanges and the need for large-scale power generation is diminished. As well as, with a decentralized network of prosumers, the grid's reserve requirements can be lowered. In terms of network losses, P2P enables energy to be consumed closer to where it is generated, by minimizing the losses associated with transmitting energy over long distances. P2P trading requires supportive regulatory frameworks that recognize and facilitate decentralized energy transactions by addressing issues such as tariffs, grid access, and the integration of distributed energy resources.

To effectively align P2P trading with grid requirements while promoting sustainability, several key strategies can be implemented. P2P energy trading is a rapidly evolving field that necessitates a thorough understanding of its limitations. Sun et al. (2024) analyze several key factors, including political, economic, social, technological, legal, and environmental aspects, offering a comprehensive understanding of the challenges and opportunities for overcoming barriers of P2P. Moreover, in the creation of a successful P2P energy system, it is important to reform unclear renewable energy regulations and to adapt to changing stakeholder roles by ensuring that P2P users are involved in policy-making and governance decisions to prevent the disruption of the system. First, a focus should be on the enhancement of the grid infrastructure with using smart grids and advanced metering technologies as key component to enable real-time monitoring and management of energy flows (Muhammad, 2024). In this context, a quick identification of imbalances and optimization of distribution is possible. According to Sechilariu (2020), smart grids, featuring advanced sensors and AI algorithms, provide enhanced control and efficiency through real-time monitoring and adaptive responses to energy demands. Moreover, integrating energy storage technology solutions - a crucial component of renewable energy integration and decarbonization of the energy system (Mohammad et al. 2023), such as batteries - can mitigate fluctuations in supply and demand, smoothing out peak demand periods and stabilizing the grid. Second, the establishment of a clear regulatory framework is fundamental for defining the roles and responsibilities of prosumers in P2P trading, covering guidelines for interconnections, grid access, and compensation mechanisms. Third, the creation of peer collaboration platforms can enhance communication and coordination among prosumers, enabling them to optimize their trading strategies, as well as maximizing their welfare and sharing of resources effectively. The promotion of policies that incentivize renewable energy adoption within P2P trading frameworks can contribute to the sustainability of energy systems.

#### 4.3. Integration with building resiliency: Leveraging infrastructure for on-site measurements

Ambient energy harvesting plays an important role in sustainable development and addresses growing environmental challenges (Pecunia et al., 2023). Therefore, a priority is the development of energy harvesting materials that can be produced with simple methods, involving low capital cost and low material and energy consumption.

The benefits of applying energy harvesting technology in wireless sensor networks are substantial, powering a network with an energy

harvester instead of a battery or wired connection, its associated maintenance and installation costs are greatly reduced. This sets the ground for new possibilities to install wireless sensor networks for data collection in all kinds of application environments (Dervojeda et al., 2014). Finally, energy harvesters reduce energy consumption and associated carbon emissions by using ambient energy which is otherwise wasted. Moreover, as stated by Dervojeda et al. (2014) wireless sensor networks powered by energy harvesters are relatively easy to install, hardly require maintenance cost, and reduce energy consumption. As investigated by the report of Sustainable Growth and EU (Dervojeda et al., 2014) these technologies are crucial in the advancement and widespread adoption of Internet of Things (IoT) devices, providing these devices with an autonomous power supply, so they can operate without relying on traditional power sources like batteries or direct electrical connections. In this framework it has some economic and social implications like cost reduction, autonomous operation, widespread development, job creation and environmental impact.

For instance, wireless sensors for water leakages are the most attractive application for small scale energy harvesting (Edvinson, 2013). These wireless sensors can be applied to detect water losses in pressurized systems, and particularly along the water supply distribution networks. In other words, these types of wireless sensors can help reduce the energy waste and water resources (Adedeji et al., 2017).

The assessments of hidden hydro technologies play an important role in providing the perspective and future roadmap of utilizing these hidden technologies, which paves the way of giving rise to commercialization and also investors' willingness to use these technologies.

#### 4.4. Summary

In Table 2, a qualitative evaluation of the main hidden hydropower technologies described in Section 3 is presented. Such evaluation is based on four characteristics: level of development of the technology, initial investment costs, maintenance costs and applicability in different countries. A quantitative evaluation (particularly of the costs) is currently not possible for new technologies which need further development and because of limited data availability on hidden hydropower in many regions of the world.

Future research on hidden hydropower technologies and their evaluation should also consider the resilience of the technologies to climate change and severe weather events. For instance, floods and sediment transport can damage some technologies (e.g., by clogging, wear) which are applied in systems where flows are not continuously controlled (e.g., open channels used for irrigation in agricultural areas). Droughts and limited (or intermittent) flow can hamper power generation, and in this case, the complementarity with multiple energy sources (e.g., solar and wind power) is fundamental to build energy systems which are more resilient to climate change (François et al., 2017; Puspitarini et al.,

**Table 1**  
Categories of possible approaches of hidden hydropower application.

	Variant A	Variant B	Variant C
Approach	Grid supply or Off-Grid consumption	Prosumer concept	Secondary advantage
Power output	Power output between several kW and lower MW range	Power output in lower kW range	Power output in W range
Pressurized systems	PAT Axial Inline turbines	PAT Counter rotating dev. Axial Inline turbines	Energy Harvester
Hidden storage	Small PSP	Counter rotating dev.	
Open channel systems	Hydrokinetic turbines	Hydrokinetic turbines Energy harvesters	

Table 2

Evaluation of the main technologies for hidden hydropower based on level of development, initial investment, maintenance costs and applicability in different regions. Note that symbols indicate high (+++), medium (++) and low (+).

Technology	Level of development/ already in the market	Initial investment	Maintenance costs	Applicability in different regions/ countries
PAT	+++	+	+	+++
Axial inline turbines (AXENT, DUO TURBO)	+	++	+	++
Classical turbines for open networks (Pelton, crossflow)	+++	++	++	+++
Siphon turbine	+++	++	+	+++
Hydrokinetic turbines	++	++	++	+++

2020).

## 5. Conclusion

The European Union (EU) is dedicated to realizing the objectives of the Paris Agreement and aims to achieve climate neutrality by 2050. A substantial transformation of Europe's energy system is necessary to attain these objectives, involving increased efficiency and deployment of renewable energy and hidden hydropower development. Expanding these technologies will create a more decentralized energy system with numerous small-scale production locations. Developing and enhancing hydropower technologies are crucial to fostering the required energy transition to meet the net-zero goals by 2050. The development of environmentally friendly and multipurpose hydropower schemes, plus utilizing additionally the untapped potential of existing infrastructure, positions hydropower as a driving force in the energy transition process.

This research study provides an evaluation of covert hydropower technologies, including their potential contribution to the transition process. Hidden hydropower presents a promising opportunity for municipalities to utilize their existing infrastructure and to decrease operational expenses for wastewater treatment facilities, water distribution systems, water treatment facilities, and irrigation systems. Investing in these technologies may achieve a more robust and environmentally friendly energy future. Indeed, hidden hydropower technologies should have a lower environmental impact on the ecosystems (in terms of greenhouse gases emissions, pollution and species endangerment) compared to hydropower produced in large water reservoirs (dams). However, future studies must investigate the environmental impacts of hidden hydropower technologies by performing life cycle assessment (e. g., Ueda et al., 2019; Gemechu and Kumar, 2022). Life cycle assessments based on accurate data and consistent modelling approaches for carbon fluxes are rare and should be applied more often, as previous studies highlighted that hydropower can be a significant source of greenhouse gases emissions, depending on the location and characteristics of the materials and the reservoirs (Gemechu and Kumar, 2022).

The paper suggests that hidden opportunities within existing facilities extend beyond their energy contribution on a large scale, emphasizing the importance of recognizing their multi-purpose benefits in optimizing water resources and existing infrastructures. These opportunities are seen as main contributors to both renewable energy and smart grid development by minimizing substantial environmental impact. The recommendation is to consider the broader advantages of such hidden opportunities for a more holistic and sustainable approach to energy and infrastructure planning.

The global deployment of 1.8 GW of off-grid capacity underscores the critical role of energy systems like solar, wind, and micro-hydroelectric plants in providing reliable electricity to remote and isolated areas, where traditional grid interconnections are uneconomical, by promoting environmental sustainability and economic development, social benefits such as job creation and enhancement of energy access.

Studies indicate that off-grid systems can be cost-effective, compared to grid electricity, which varies widely in price. Specifically, technologies like pressurized water systems, Pump Storage Plants (PSP), and hydrokinetic turbines offer enhanced efficiency and productivity by

contributing to the economic viability of renewable energy projects as well as to the new energy transition model. Also, integrating micro hydroelectric plants in rural areas provides affordable, reliable electricity, reduces reliance on fossil fuels, and creates employment opportunities, thus supporting local economies.

Furthermore, the concept of prosumers plays a pivotal role in decentralization of energy production, facilitated by technologies like PATs through P2P trading platforms and enhancing energy self-sufficiency and grid resilience. In this context, contributions in the sustainability and efficiency of energy systems are made by innovations in ambient energy harvesting and wireless sensor networks, highlighting the importance of continuous investment in these technologies towards a low carbon future.

In addition, increasing electricity production with small-scale hydropower will mitigate dependency on the national energy system for water supply utilities, by lowering their energy costs.

The field of hidden hydropower technologies still needs intense multidisciplinary research and development contributions in several key areas to enhance their design, efficiency, and integration into existing water distribution systems. One priority is the development of more compact, efficient, and cost-effective turbines tailored specifically for these systems, with careful consideration given to identifying optimal locations for installation that do not disrupt water supply or compromise infrastructure. Additionally, substantial research effort should be devoted to optimization models and algorithms to maximize energy recovery while minimizing operational impacts, leveraging real-time monitoring tools and AI-based predictive analytics to adapt to varying flow rates and demands.

Further investigation is needed into the potential synergies between hidden hydropower and other renewable energy sources, such as solar or wind, and how these technologies can be integrated to enhance sustainability in water networks. Finally, future studies must address the economic feasibility and scalability of these systems, particularly in low-income countries, by developing funding models and incentives that encourage water utility companies to invest in hydropower solutions.

One of not only research, but also practical challenges in hidden hydropower lies in integrating these systems into existing infrastructure without significant modifications (minimum impact on current pipelines, minimum civil works).

Navigating policy and regulatory barriers is also essential, as streamlined permitting processes and favorable policies for renewable energy integration will be key to advancing these technologies. Establishing frameworks that allow utilities, but also individuals to sell surplus power back to the grid can further promote adoption. This also concerns prosumer concepts (P2P schemes). Collaboration between the public and private sectors is crucial for scaling these solutions, with research needed to explore partnership models and incentive structures that align the interests of both parties. Last but not least it should be emphasized that the development of pilot projects and demonstration sites is essential for gathering data on performance, economic viability, and public acceptance, ultimately accelerating the widespread adoption of hidden hydropower technologies.

## CRedit authorship contribution statement

**Martin Seydoux:** Writing – original draft. **Eduard Doujak:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Giulia Zuecco:** Writing – review & editing, Conceptualization. **Aldo Leonardo Alerci:** Writing – original draft, Validation, Investigation. **Alex Trojer:** Writing – original draft, Visualization, Project administration. **Marija Lazarevikj:** Writing – original draft. **Pavel Rudolf:** Writing – review & editing, Supervision, Conceptualization. **Valbona Karapici:** Writing – original draft, Investigation, Conceptualization. **Tomáš Pluskal:** Writing – original draft, Investigation. **Anna Chernobrova:** Writing – original draft, Investigation. **Emir Neziric:** Writing – original draft, Visualization, Investigation.

## Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Eduard Doujak reports article publishing charges was provided by TU Wien University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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## Data Availability

No data was used for the research described in the article.

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