Energy harvesting from municipal water management systems: from storage and distribution to wastewater treatment

Daniele Novara
daniele.novara@tecnico.ulisboa.pt
Instituto Superior Técnico, Lisboa, Portugal
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ABSTRACT: Water and energy are among the fundamental resources at the basis of human life and society development. Their strong interrelation in many human activities has been referred to as “Water-Energy Nexus” and has been subject of growing interest during the last decades. Within the first part of the dissertation the extents of such nexus are reviewed, providing a description of hydropower sector and relative technologies as well as presenting the scopes and needs of water supply systems. The second part of the work instead is focused on the investigation of energy recovery potential from water supply and treatment facilities. Such supply systems in fact rely on large amounts of electricity to pump, treat and distribute water. However, situations can occur where fluid holds an excess energy that can be converted back into electricity instead of being dissipated. Three real case-studies have been analyzed in collaboration with water companies from Italy and United States in order to derive a feasibility study of energy harvesting from:

- sections of a water distribution network, installing a pump in reverse mode (PAT) as replacement or complement of a Pressure Reducing Valve (PRV);
- pressurized water flow at entrance of an elevated storage tank, by installing a PAT in a by-pass duct;
- outlet flow from a wastewater treatment plant passing through an open-air channel, by means of a hydrostatic energy converter.

The chosen case-studies have been assessed from different perspectives, including a technical analysis as well as economic and environmental when possible.

Key-words: Hydropower, Hydrostatic Pressure Machine (HPM), Pumps as Turbines (PAT), Water-Energy Nexus, Water Supply Systems (WSS)

1. SCOPE AND STRUCTURE

Energy and water are basic resources whose availability and quality are strictly connected to human lifestyle and development of society. In sight of the future challenges ahead of us and the need to cope with scarcity of such resources is therefore fundamental to optimize their exploitation in an innovative and multidisciplinary way.

The aim of the present dissertation is to investigate opportunities for energy harvesting from water treatment and distribution networks analyzing in details three real case-studies in partnership with industry, providing at the same time an overview of water and energy sectors. The chosen structure of the document is displayed in Figure 1.

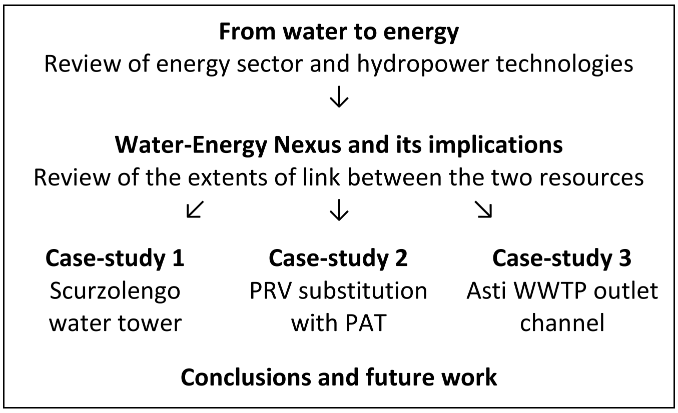

Figure 1 - Structure of the dissertation

2. FROM WATER TO ENERGY

World energy sector

At present days most of the world energy demand is supplied by fossil fuels, which in 2014 accounted for around 68% of electricity production around the globe [1] as shown in Figure 2.

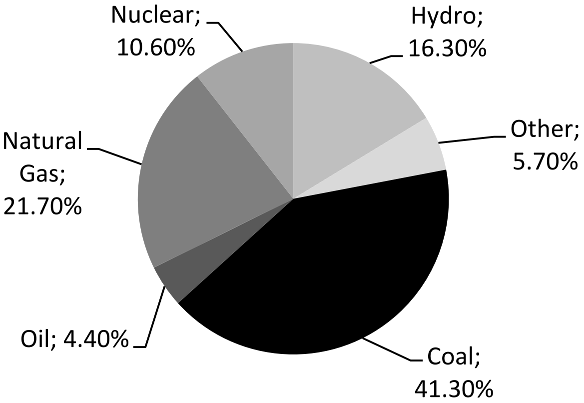

Figure 2 - Shares by fuel of electricity world production in 2014 **[1]**

However, a high dependence on fossil fuels proved to be unsustainable in the long run because of physical limit of resources [2], environmental issues [3], economic instabilities and political concerns regarding security of supplies. Besides, the fossil-origin CO_2 released during combustion processes is considered by most scientists as major cause of greenhouse effect and global warming which is likely to cause adverse health impacts on more vulnerable social groups [4] and increase occurrence of extreme meteorological events [5].

As a result of the efforts made to decouple economic prosperity from emission of greenhouse gases significant global trends in energy sector of industrialized countries are emerging, namely the diffusion of renewable technologies and the switch from centralized power systems to distributed or hybrid systems which integrate small-scale diffuse energy generation technologies [6]. Moreover, as demonstrated among others by Kanase-Patil et al. [7], distributed power systems based on renewable sources are a practical and cost-effective solution for off-grid rural electrification in developing countries.

Hydropower technologies

Hydropower, together with biomass, is the renewable energy whose technology is more mature and reliable. It is a non-intermittent energy source capable of contributing both to base load and peak load (through building of a reservoir) and, for pumped plants, able to store energy. Hydropower technology has proved to be one of the most cost-effective, with long lifetime and reduced maintenance needs with respect to other “green” generation technologies [8].

Large hydro plants have been built in Europe and USA since the end of 19th century, greatly contributing to the development of industrial sector and the electrification process. Nowadays big hydro facilities are still being built in many developing countries, while in industrialized ones most locations with ideal conditions have already been exploited and market for large-scale plants has almost reached saturation. However, current economic conditions and the impulse towards a CO_2-free energy generation mix are leading to implementation of small scale hydro plants all over the world [9].

Hydropower plants are commonly divided into categories according to the facility type and the range of installed power.

As for the first criteria, four different layouts are usually adopted:

- Impoundment hydro plants
- Run-of-River plants
- Pumped storage plants
- In-stream hydropower schemes

As for the plant size, several categories have been proposed:

- Large Hydro
  a generally accepted definition classifies as “large” plants those with nominal power greater than 10MW;
- Small Hydro
  with installed power in the range between Micro and Large Hydro;
- Micro Hydro
  which generate less than 100kW of power;
- Pico Hydro
  with less than 10kW of installed capacity.

Apart from conventional water turbines, a large number of different hydraulic machines has been studied and/or implemented to generate energy exploiting fluid streams having low hydraulic energy. Such condition is generally due to low available heads (H) or reduced volumetric flows (Q), which is a common situation in many practical cases when installation of a traditional turbine unit would prove to be unfeasible or uneconomical. For instance, in 2005 Giesecke and Mosonyi [10] showed that in Europe only 30% of theoretically available hydropower potential remains unexploited, which is mainly constituted of sites with head drops in the range of 1-3 meters. Tidal water flows correspond to those characteristics, as well as the tens of thousands of locations across EU countries where in the past watermills were installed which nowadays remain unused [11]. Also, possibility of harvesting potential of water flowing in pipes or in open channels often depends on the availability of specifically designed equipment.

While large hydro plants around the globe are powered by conventional hydraulic turbines, for schemes with less than 100 kW of installed power a vast range of machinery is either available on the market or being studied. An overview of possible technologies is shown in Figure 3.

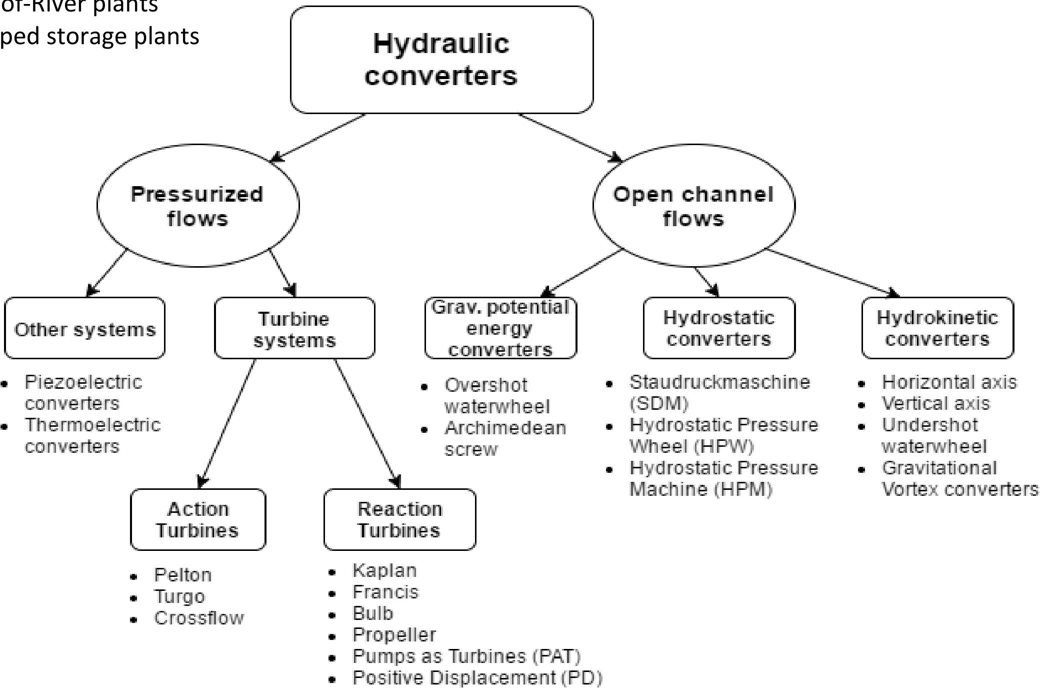

Figure 3 - Overview of hydropower technologies

Basic concepts of hydraulic machinery

Hydraulic machinery is specifically designed to convert energy of a fluid stream into rotating mechanical energy. Power output of a hydraulic machine is defined as:

$$P = \eta\, g\, \rho\, H\, Q \qquad (1)$$

where:

P: power output (W)
η: machine efficiency (-)
g: gravitational acceleration, equal to 9.81 (m/s^2)
ρ: fluid density (kg/m^3)
H: net head (m)
Q: nominal flow rate (m^3/s)

In turbomachinery performance analysis affinity laws are widely used to express relationship existing between power and other interrelated parameters. The concept of specific speed (Ns) is used to distinguish families of geometrically similar machines, defined as follows:

- according to discharge value, for pumps or turbines

$$Ns,q = N\frac{\sqrt{Q}}{H^{3/4}} \qquad (2)$$

- according to power, for turbines

$$Ns,p = N\frac{\sqrt{P}}{H^{5/4}} \qquad (3)$$

where:

N: rotational speed (rpm)
H: available head (m)
Q: flow rate (m^3/s)
P: power at shaft (kW)

For a family of geometrically similar pumps or turbines (i.e. having the same specific speed) it is possible to relate between them the main characteristic parameters through affinity laws [12]:

$$\frac{Q'}{Q} = \frac{N'}{N}\left(\frac{D'}{D}\right)^3 \qquad (4)$$

$$\frac{H'}{H} = \left(\frac{N'}{N}\right)^2\left(\frac{D'}{D}\right)^2 \qquad (5)$$

$$\frac{P'}{P} = \left(\frac{N'}{N}\right)^3\left(\frac{D'}{D}\right)^5 \qquad (6)$$

Pumps as Turbines (PATs)

Pumps as Turbines (PATs) are an unconventional solution for hydro power generation adapt to fit in many scenarios when a conventional turbine unit would not be suitable. Physical behavior of PATs is similar to Francis turbines, but without possibility for flow regulation. A representation of centrifugal PAT is shown in Figure 4.

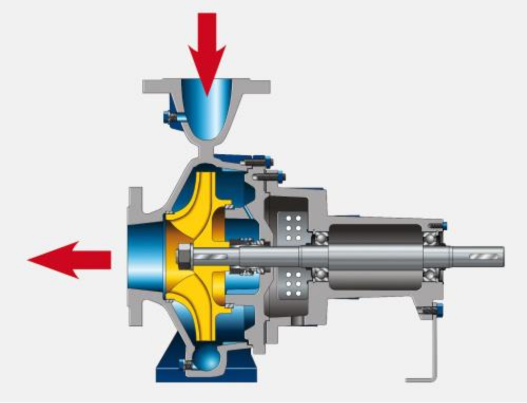

Figure 4 - Drawing of centrifugal PAT
[csmres.co.uk/cs.public.upd/article-images/Fig-3-55016.jpg]

Within last decades large numbers of PATs have been studied and implemented as power generators in many contexts like small hydropower schemes with low-head properties, Water Supply Systems (WSSs) and industrial applications as replacements of throttling valves. In particular, they proved to be very effective if used for micro hydro off-grid plants and in-pipe energy recovery [13], [14].

The use of PATs proved to have several advantages over other turbine types:

- generator units composed of pump and shaft-connected induction motor present more compact dimensions than most conventional solutions;
- mass manufacturing of pumps makes them easily available in large number of standard sizes and characteristics, suitable to most application cases;
- short delivery time;
- they present easy installation, operation and maintenance and relative spare parts are easily available;
- they have a longer life span with respect to other small-size hydraulic turbines as shown by Williams [13];
- the capital requirements needed to cover investment costs are generally lower than traditional turbines which are built as unique units according to site specifications [15];
- they are a widely studied technology with proven results [16].

Despite the above mentioned positive aspects, two major challenges need to be overcome to allow for a wider application of PAT technology:

- normally producers don't provide customers with PAT turbine characteristic charts, thus analytical methods need to be applied to estimate them [17];
- centrifugal pumps do not offer possibility for flow rate regulation. As a result, they are characterized by poor part-load performances.

Graphical representation of typical performance curves for a radial pump in both operation modes is shown in Figure 5.

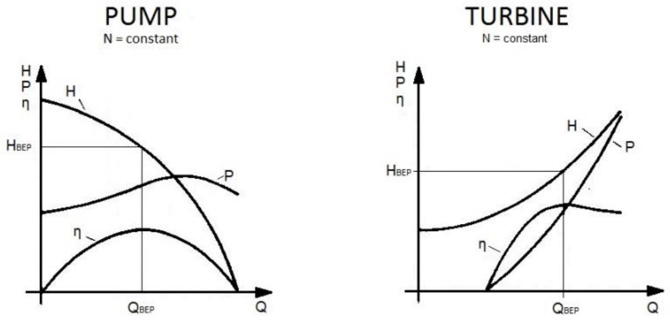

Figure 5 - Typical performance curves of pumps and turbines **[15]**

One of the major obstacles to widespread PAT adoption is the little information available regarding turbine operations of commercially available pumps. To overcome such limitation a series of methods have been proposed by various authors. As reviewed by Agarwal [18] and Nautiyal [19], several mathematical methods exist to correlate H-Q coordinates of BEP between pump and turbine mode based on maximum efficiency and specific speed Ns.

Specifically, three nondimensional coefficients relating BEP characteristics in turbine or pump mode have been proposed:

$$h = \frac{H_{t,BEP}}{H_{p,BEP}} \quad q = \frac{Q_{t,BEP}}{Q_{p,BEP}} \quad p = \frac{P_{t,BEP}}{P_{p,BEP}} \tag{7}$$

As shown by Carravetta et al. [20] and Páscoa et al. [21], Computational Fluid Dynamics (CFD) analysis can also be an effective tool for prediction of PAT turbine mode characteristics. In spite of its potentially high computational complexity, it also enables analysis of machine operations under transient hydraulic conditions.

Besides, as stated by Singh [17] and Bogdanović-Jovanović et al. [22], CFD analysis allows for evaluating how internal pressure losses are distributed along the PAT control volume. Such knowledge is extremely valuable in order to identify possibilities for performance optimization as rounding the inlet impeller or enlarging the suction eye.

Hydrostatic Pressure Wheel/Machine (HPW/HPM)

A Hydrostatic pressure wheel operates because of the difference in static pressure from upstream to downstream occurring in a water body when a drop in fluid level is present. Pressure acts on a vertical surface immersed in water with a depth h (m) along a hydrostatic pressure distribution whose vectors can be calculated as:

$$p = \rho\, g\, h \tag{8}$$

where:

p: relative pressure (Pa)
ρ: fluid density (kg/m3)
g: gravitational acceleration (m/s2)

The theory behind HPM is based on the formulations developed by Senior et al. [11] regarding the ideal Hydrostatic Pressure Wheel having infinite radius. The HPM is also referred to as "dam effect waterwheel" [11], since the difference in water level from upstream and downstream is equal to the hub diameters and can be maintained by the machine without the need of a sluice gate. The idealized operation scheme of HPM is shown in Figure 6.

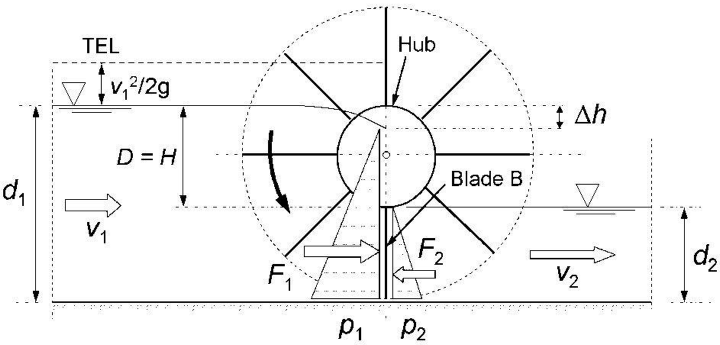

Figure 6 - Working scheme of HPM (adapted from **[23]**)

where:

D: hub diameter, corresponding to water level difference d1-d2 (m)
v1: upstream velocity (m/s)
v2: downstream velocity (m/s)
F1: force on the blade along the fluid direction (N)
F2: reaction force on the blade (N)
d1: upstream water level (m)
d2: downstream water level (m)
TEL: Total Energy Line (m)
Δh: head difference due to fluid acceleration from v1 to v2 (m)

As stated by the report by Schneider et al. [23], the power output per unit width of an ideal machine can be described as:

$$P_i = v_2(F_1 - F_2) = \rho\, g\, d_2\, v_2 \left[d_1 - d_2 - \frac{v_1^2}{2g}\left(\frac{d_1^2}{d_2^2} - 1\right)\right] \tag{9}$$

Assuming that the maximum flow rate that an ideal machine can process corresponds to a zero power output and considering the upstream velocity as negligible the maximum flow velocity can be approximated as:

$$v_{max} = \sqrt{2\, g\, (d_1 - d_2)} \tag{10}$$

Therefore, the maximum theoretical flow rate per unit width is equal to:

$$Q_{max} = v_{max}\, d_2 \tag{11}$$

To account for the real working conditions of a similar hydrostatic wheel, according to the research done by Schneider et al. [23], additional terms must be introduced into the previous equations to account for:

- leakage losses caused by water infiltrating between the blades and the fixed shroud structure;
- turbulence losses caused by interactions between moving blades and water;
- acceleration losses due to acceleration of water when entering the HPM.

3. WATER-ENERGY NEXUS

The term Water-Energy Nexus (WEN) refers to the relationship between the use of water for energy production and the efforts necessary to collect, treat, and transport water. It's been a subject of growing interest in academic and industrial contexts along last decades, with efforts aimed at acquiring an integrated and systemic view on the two sectors (water – energy) [24].

As shown, water plays a key role in the energy production portfolios worldwide. Not only hydropower is the most exploited renewable energy source around the globe, but every thermal power plant (both relying on fossil fuels or nuclear fission) requires significant amounts of water to cool down working fluids and perform efficient thermodynamic cycles. Also, satisfying irrigation needs is fundamental for growing crops which provide food or biofuels. At the same time, water companies consume substantial amounts of energy to ensure a safe, reliable and environmental-friendly water supply to the served consumers.

WEN on large scale

A well-known example of Water-Energy Nexus (WEN) on a large scale is the common practice of building artificial reservoirs with dual purpose, able to supply water to nearby communities and feed hydro power plants in a way which is reliable and independent from hydrologic regimes. A recent example of such approach is the Alqueva Multi-purpose Project in the Alentejo region of Portugal. Built in two phases (I and II) and completed in 2013, it consists in the creation of an artificial lake with around 250km^2 of surface along Guadiana river whose waters supply a 520MW power station besides satisfying needs for water supply and irrigation over a large territory [25].

WEN on medium-to-small scale

A modern water management system consists in performing and optimizing a series of tasks and activities essential to provide a fundamental service to communities.

Fresh water is firstly pumped from a reservoir (underground aquifers or surface water bodies) to a treatment station in order to meet the parameters set for human consumption. Subsequently it is fed into transport and distribution networks to reach end users. At the same time, a sewage network collects wastewater and conveys it to a treatment plant where its contaminant charge is reduced before release into the environment. A simplified scheme of an integrated water management system is shown in Figure 7.

The above described water system is characterized by substantial requirements for electricity in all of its phases in order to pump, treat, store, monitor and transport water. Modern water companies are large consumers of energy and during the last 20 years have been facing continuous growth in energy requirements as shown by the report by Pabi et al. published in 2013 [26].

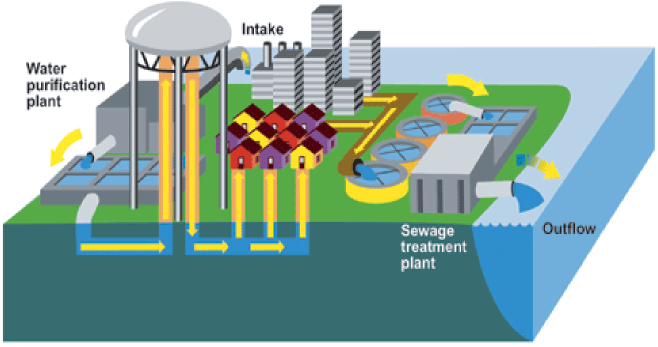

Figure 7 - Municipal water supply and sewage treatment scheme [waterconservationwasting.weebly.com]

As a way to reduce energy consumption of water utilities growing interest is been raised on exploiting water for drinking or irrigation purposes flowing in pipes or channels to produce electricity. As reviewed by McNabola et al. in 2014 [27], micro-hydropower schemes are an effective solution for energy recovery from WSS and several researches carried out in the past highlighted a series of recurrent situations within water networks from which energy can potentially be recovered:

- excessive pressure in correspondence of inlet ducts leading into storage reservoirs;
- excessive pressure within gravity-fed water conveyance pipes;
- substitution or replacement of Pressure Reducing Valves (PRVs) with PATs;
- dissipated potential within irrigation networks;
- sites at inlet or outlet of Wastewater Treatment Plants (WWTPs) characterized by low available net heads albeit showing significant and constant flow rates throughout the day.

WEN on micro scale

On a micro scale, energy harvesting from water distribution networks is believed to be an effective solution to power wireless sensors or equipment located along the pipes in isolated zones [28].

4. CASE-STUDY 1: SCURZOLENGO WATER TOWER

The concrete-made water tower analyzed within this research is located in the area of Scurzolengo municipality in Asti administrative region, Italy. It is situated on a hilltop at altitude of 265 m AMSL (Above Mean Sea Level) and stands out of the ground for 24 m. The conic tank capacity is equal to 250 m^3 with a maximum inner water height of 3.97 m. In Figure 8 is shown a screenshot of SCADA remote control system visualizing parameters of inlet flow and water level inside the tank as seen from control room. A sample of pressure and flow rate parameters at the tower basis is recorded every 15 min and can be observed in real-time by the facilities of the Monferrato aqueduct control room located in the municipality of Moncalvo.

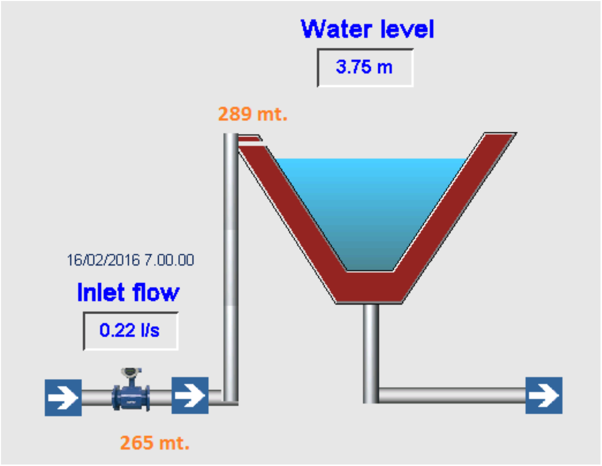

Figure 8 - SCADA view of flow and water level parameters

Within the stipulated agreement a database containing data covering the timeframe of a week between Tuesday 9th of February 2016 and Monday 15th of February of the same year could be accessed. In the following Figure 9 and Figure 10 are presented diagrams of inlet water flow, upstream pressure and tank level relative to Thursday 11/2/2016.

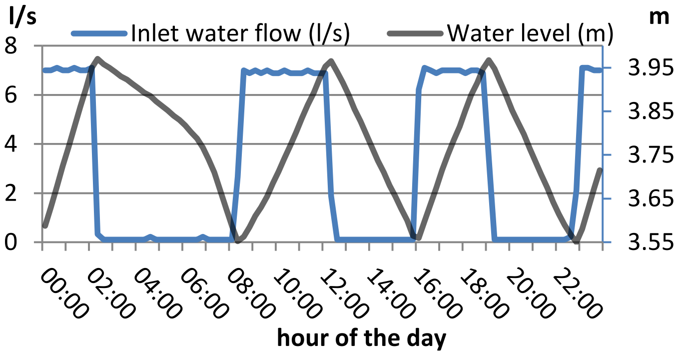

Figure 9 - Recorded values of inlet flow and water level (11/2/2016)

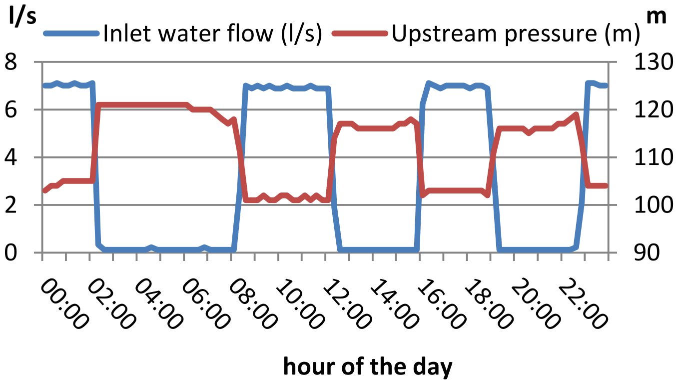

Figure 10 - Recorded values of inlet flow and upstream pressure (11/2/2016)

The design parameters to proceed with machinery selection are:

- H (available head) = 74.94 m
- Q (flow rate) = 7 l/s

A schematic view of the proposed PAT installation is shown in Figure 11. The number 1 marks the existing self-driven valve regulating water inlet to the tank, while number 2 refers to the manual sectioning valves of proposed installation. Instead, the motor-driven valve of new installation marked as 3 is designed to remain close during normal operations and open only when the level inside water tank lowers below a minimum value set by the water company.

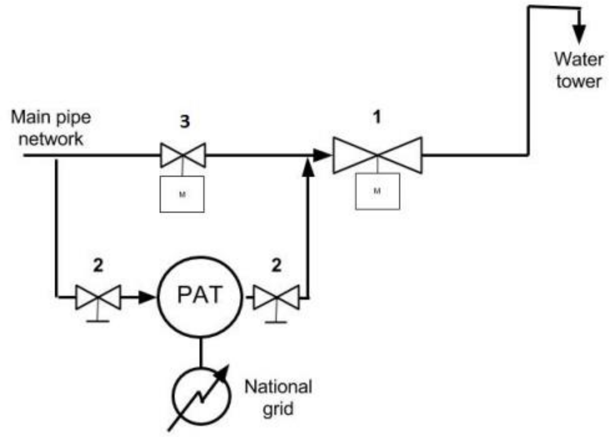

Figure 11 - Proposed PAT installation layout

Through the Cordier diagram as developed by Singh [17] optimal single-stage PAT characteristics matching with design parameters were found as:

- pp = 1
- N = 3000 rpm
- D = (154 ± 12) mm

Given the commercial unavailability of characteristic curves of multistage pumps adapt to the context, as basis for further calculations was used a centrifugal pump ETANORM 50-32-160.1 by manufacturer KSB having D=176 mm of which turbine mode characteristic curve was reported in Master's Thesis dissertation by Tânia Calado [12]. Such unit was selected because of its parameters which are similar to the optimal calculated ones and, furthermore, because both characteristic curves as pump and as turbine issued by its producer were available [29].

The results of technical analysis show than the total producible energy over a typical year is equal to 9585 kWh, distributed over the twelve months as shown in Figure 12.

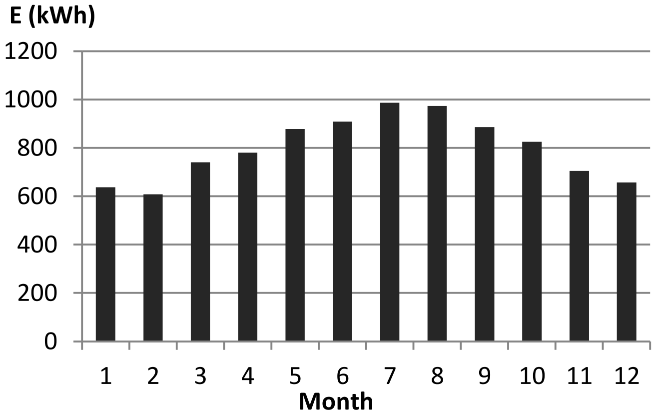

Figure 12 - Total producible energy over a typical year

A simple payback period analysis was carried out based on different scenarios of energy remuneration in order to assess the feasibility of the proposed installation. Regardless of the presence of incentives, the payback time for the needed investment lays between the beginning and the end of Year 2 when the generation plant is considered to start operations in January. Another important parameter to assess the convenience of energy systems is the Levelized Cost Of Electricity (LCOE), defined as the ratio between the sum of all costs over the lifetime of a determined production technology and the total generated electrical energy. For the proposed installation, considering the PAT lifetime being 20 years and setting a discount rate equal to 5% a LCOE value of 0.025 €/kWh is obtained.

Avoided emissions of particulate matter, NOx and CO2 over a year relative to the proposed scheme are summed up in Table 1 [30], [31].

Table 1 - Estimated avoided emissions over a year relative to the studied PAT plant

Type of avoided emission	Quantity	Unit
CO_2	3.13	tons/year
Particulate matter	28.76	g/year
NO_x	2.97	kg/year

5. CASE-STUDY 2: PRV REPLACEMENT WITH PAT

In collaboration with Rentricity Inc., an algorithm was developed based on Variable Operating Strategy to select the optimal PAT characteristics and installation layout to replace an existing PRV station.

As already reported by Ramos and Borga in 1999 [32], an effective application field of PATs is the replacement or coupling with Pressure Reducing Valves (PRVs) inside water distribution pipelines.
However, as previously stated one of the main limitations to PAT usage is the lack of flow rate regulation possibility due to the lack of guide vane. As a result, their implementation alone within water supply systems characterized by periodical flow rate and available head variations can lead to:

- reduced global power output due to low part-load efficiency
- impossibility to ensure the required head drop under all operating conditions

Recent researches by Carravetta et al. published between 2012 and 2013 [33], [34] and [35] aimed at defining a procedure named VOS (Variable Operating Strategy) to enable selection of the optimal PAT to be installed in series or in parallel with PRVs in order to maximize energy production from a specific site while meeting the requirements set by network operator/management. Given the absence of flow regulation possibility within the pump-generator unit, three alternative designs have been investigated:

1. Hydraulic Regulation (HR), in which a PRV placed in series with PAT and a by-pass circuit allow the turbine to work in the surrounding of BEP;
2. Electric Regulation (ER), when the operating pump speed N can be adjusted thanks to a connected inverter;
3. Hydraulic and Electric Regulation (HER), when both previous regulations are implemented.

A simplified installation scheme of both HR and ER configurations is presented in Figure 13 below.

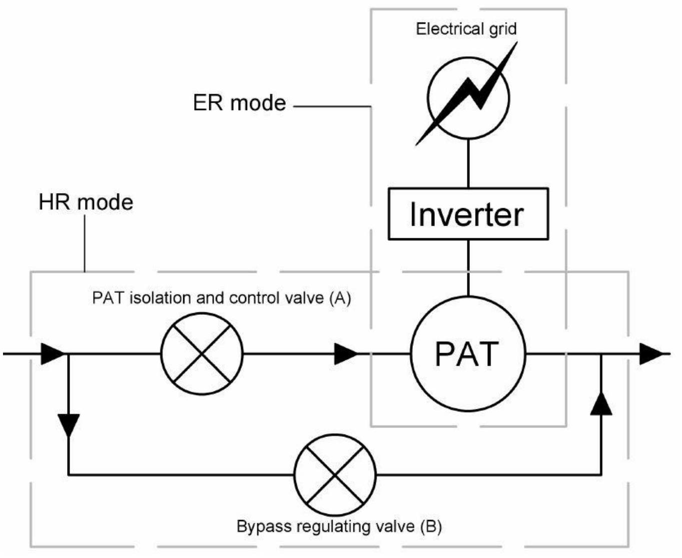

Figure 13 - Installation scheme of PAT with Hydraulic and Electric regulation **[34]**

As target for maximization the plant overall efficiency over "n" working points has been set as:

$$\eta_p = \frac{\sum_{i=1}^{n} 9.8\, \eta_i^T\, Q_{t,i}\, H_{t,i}\, \Delta t_i}{\sum_{i=1}^{n} 9.8\, q_i\, h_i\, \Delta t_i} \qquad (12)$$

where:

q, h: volumetric flow rate and available head present in the system (m^3/s, m)
Q_t, H_t: volumetric flow rate and head drop through the PAT (m^3/s, m)
η_i^T: PAT efficiency (-)
Δt: time interval (h)

The available data about PRV installation includes water flow rate and upstream and downstream pressure variations along a typical day. The profiles of flow rate and head drop across the valve are shown in Figure 14.

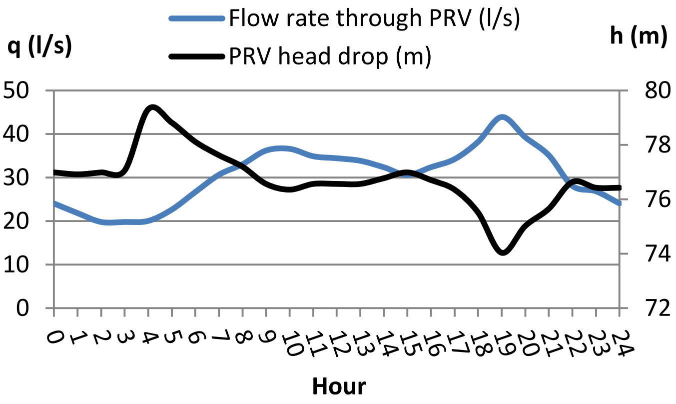

Figure 14 - Flow rate and head drop across PRV along a typical day

Following the methodology developed by Carravetta et al. [33], [34] and [35] it was decided to analyze the most appropriate PAT to be fitted in the system according to two alternative design strategies:

1. PAT alone as replacement of PRV;

2. PAT added in series to the PRV and with flow by-pass channel, to allow for Hydraulic Regulation which Carravetta et al. [34] showed being the most effective regulation strategy.

The calculations were carried out and aimed at individuation of PAT impeller diameter D and rotational speed N which lead to the maximum overall plant efficiency η_p as described in Equation 12. The characteristic curves of PATs having different D and N were obtained using the turbomachinery affinity laws based upon the data collected by Singh [17] relative to nine centrifugal, single stage machines experimentally tested plus the KSB ETANORM 50-32-160.1 turbine analyzed for previous case-study.

Results of the performed analysis match well with the referenced literature, showing a significant increase in producible energy when possibility of flow regulation is introduced (namely, Hydraulic Regulation). Despite the higher installation and maintenance costs due to addition of a PRV in series to the PAT and the realization of by-pass pipe, the yield of such a configuration is significantly higher than the simple PAT installation as replacement of PRV. Also, another advantage given by HR scenario is the possibility for the water network operator to set and maintain an optimal value of downstream pressure independently of the flow rate which is not possible in the scenario without regulation.
The variations in the maximum attainable value of ηp along the two considered scenarios are summed up in Table 2.

Table 2 - Maximum attainable ηp for the considered scenarios

	N = 1520 rpm	N = 3020 rpm
No flow regulation	27%	37%
HR	35%	57%

Since no further information was available regarding the context of the analyzed PRV station (e.g. location, specific requirements from the network operator, electricity costs, space constraints) it was decided to limit the analysis to technical considerations and disregard the economic and environmental aspects. However, when selecting the PAT characteristics for installation within a precise PRV site it would be appropriate to perform an optimization based on economic parameters instead of merely technical ones (ηp). Also, an appropriate and site-specific environmental analysis is recommendable.

6. CASE-STUDY 3: Asti WWTP

In collaboration with water company ASP, the installation of an energy recovery device into the outlet of a WWTP was investigated. After a visit to the plant which took place on 11th of February 2016, together with ASP management it was agreed that the site offering the highest potential for energy harvesting is the concrete-made open air channel through which purified water in conveyed. Here, soon after a Venturi Flume flow meter, the channel bed drops by 80 cm and water enters a DN800 pipe.

A 3D view of the terminal part of the channel is presented in Figure 15.

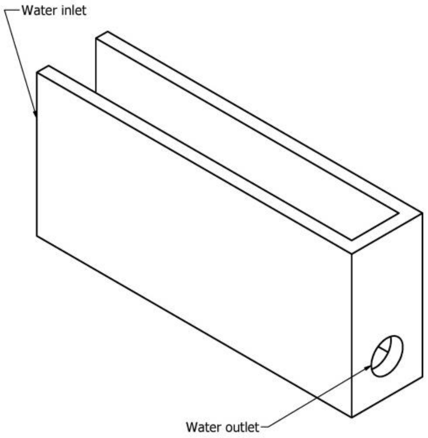

Figure 15 - 3D isometric view of WWTP channel

The water flow rate through the investigated WWTP outlet channel presents a high variability during different times of the day, with higher values from 10 a.m. to midnight and lower flow rates between 1 and 9 a.m. as shown in Figure 16 together with the corresponding water depth at Venturi intake.

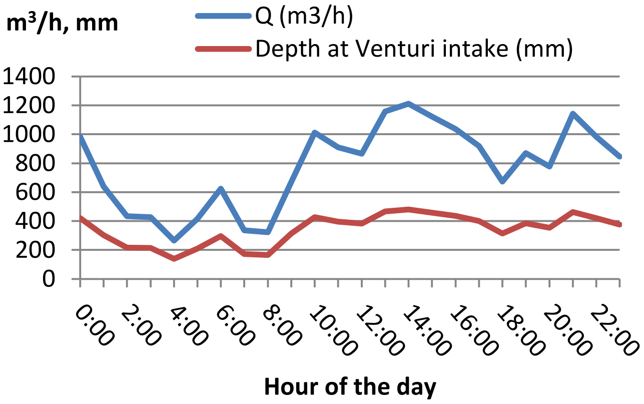

Figure 16 - Water flow rate through WWTP outlet channel and depth at Venturi intake on 12/4/2016

The design characteristics of the analyzed open channel can be summarized as:

- flow rate Q ranging from around 0.07 up to 0.83 m^3/s during extreme meteorological events
- available head comprised between 62 and 744 mm

Given the site specifications, the most promising technology was selected to be the Hydrostatic Pressure Machine (HPM) which is an experimental waterwheel design specifically meant for application in open channels with reduced head differences, having the advantages of small size and not requiring additive hydraulic elements (e.g. weirs to regulate fluid depth). The HPM unit includes the wheel, a metallic support structure and a bottom shroud to ensure that at any given moment a water section included between two adjacent blades is enclosed and separated from the rest of fluid. A visual representation of water flow through the HPM is displayed in Figure 17,

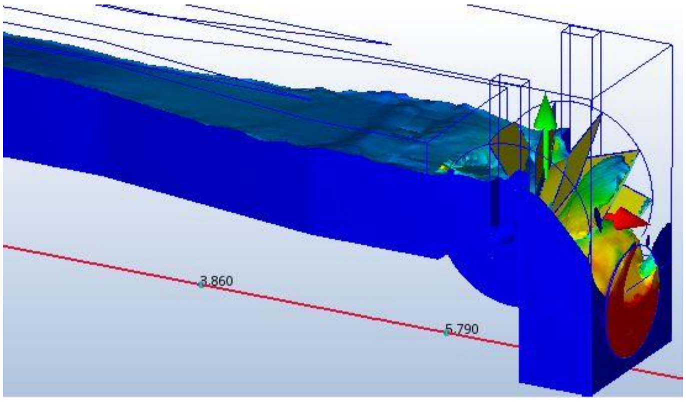

Figure 17 - Axonometric view of water flow through the Venturi Flume and HPM

Given the design requirements, the maximum volumetric flow that can be processed by a similar machine is equal to about 430 l/s which is higher than the maximum flow rate occurring during a precipitation-free day. However, since under exceptional conditions a maximum of 833 l/s must be able to flow through the channel the construction of an additional by-pass is required. The simplest design comprises a side opening in the concrete structure with crest at the same level of the top of HPM hub plus a side chamber discharging to a pipe to be connected to the main DN800 duct.

The characteristic curve of the studied HPM unit presented in Figure 18 has been evaluated using as inputs the adimensional coefficients estimated during lab testing campaign of the same machine carried out under the HYLOW program [36].

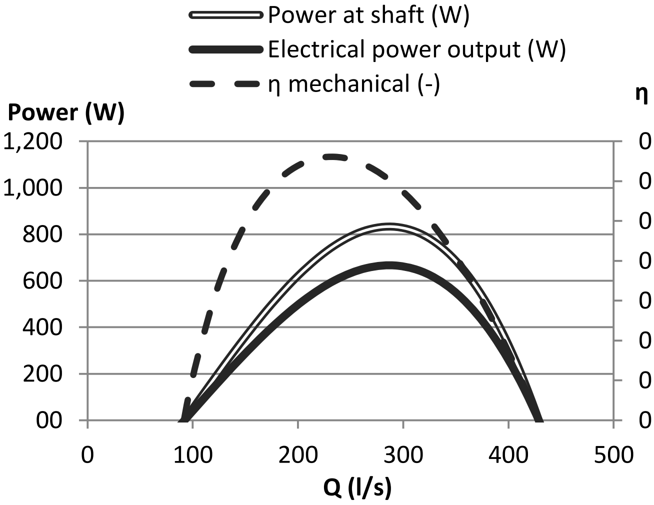

Figure 18 - Characteristic curve of the designed HPM unit

A discounted payback period analysis was carried out based on different scenarios of energy remuneration and discount ratio in order to assess the feasibility of the proposed installation. Six different scenarios have been evaluated to estimate the discounted payback period under different assumptions, namely:

- availability or unavailability of incentives;
- discount ratio equal to 2, 6 or 8 %.

Results from the chosen scenarios are summed up in Figure 19, where values of Cumulative Discounted Cash Flow (CDCF) are plotted against the project timeline selected as 20-years long. The discounted payback period is graphically equal to the year at which the traced functions intersect the CDCF=0 horizontal line.

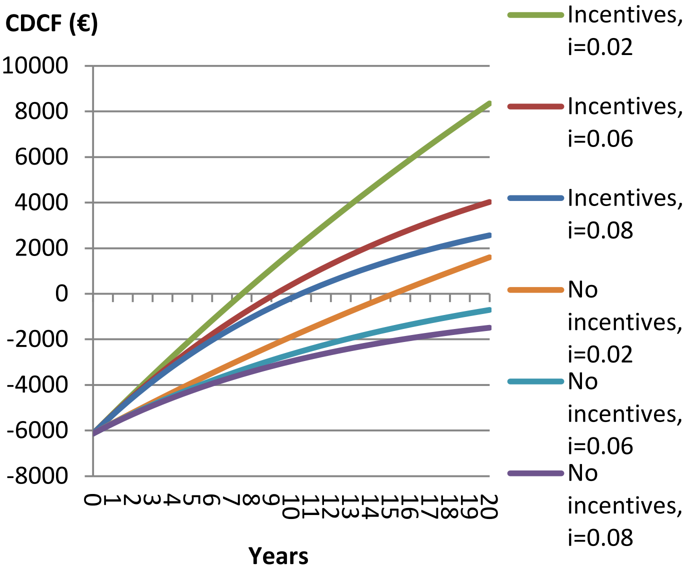

Figure 19 - CDCF plotted versus project timeline under six analyzed scenarios

7. CONCLUSIONS AND SCOPE FOR FUTURE RESEARCH

As clearly emerged both from literature review and the examined case-studies, micro-hydropower installations to be placed within water supply systems can give a significant contribution towards a less energy intensive, CO_2-free, sustainable and reliable future water sector. Installing such hydropower plants could allow for the recovery of potential energy otherwise dissipated and provide water utilities and communities with significant economic and environmental benefits.

The development of innovative and efficient technologies for micro and pico-hydropower is a key challenge in order to reach the mentioned targets, since little knowledge and expertise is currently available on such small turbines with respect to the great achievements made in the field of medium-to-big size hydropower converters. Besides, micro-hydropower generators can have a significant application field within rural electrification programs in both developed and developing countries and off-grid distributed energy systems.

Case-study 1: Scurzolengo water tower

The preliminary study carried out to evaluate the installation of a PAT unit to exploit overpressures occurring in correspondence of water inlet into an elevated storage tank showed interesting environmental and economic parameters, with payback period lower than two years within all the analyzed scenarios. As a further advantage, network operator is familiar with the proposed technology and a significant knowledge is available on such installations worldwide. The present study could be expanded and complemented in order to consider more aspects and increase the accuracy of analysis. Possible future developments may include:

- gathering additional data about variation of pressure and flow profiles during summer months, since the higher seasonal water demand could possibly lower the pressure within the network and influence the design parameters;

- evaluating the installation of an inverter coupled with the PAT unit to modulate the water flow entering the tank;
- considering the adoption of a multistage unit instead of the analyzed simple centrifugal PAT, which could possibly attain higher efficiencies respect to the considered solution.

Case-study 2: PRV substitution with PAT

The installation of PAT units as a replacement or complement of PRV stations within water networks proved to be a technically feasible and efficient solution. Schemes including a water bypass and a PRV assembled in series with a PAT (HR) showed a higher electricity yield with respect to mere PRV substitution with PAT, besides allowing network operators to set and maintain a constant optimal backpressure.

Further developments of the presented study can include:

- improving the available database including characteristic curves of additional PATs having different specific speed;
- developing an algorithm allowing for finding the optimal characteristics of a PAT in terms of installation scheme, impeller diameter and specific speed based on economic parameters (maximizing CDCF or minimizing the payback period). Results of such analysis could be compared with the PAT characteristics corresponding to highest electricity yield.

Case-study 3: Asti WWTP

Despite the significant and guaranteed daily water flow passing through the examined WWTP outlet channel, the extremely low available head causes an hypothetical HPM installation to perform low in terms of generated electricity and economic attractiveness. In particular, discounted payback period has been evaluated as equal to 8 years within the most optimistic scenario and higher that 20 years for the worst configuration of parameters.

Additional developments to the actual preliminary study could involve:

- computational Fluid Dynamics (CFD) studies to identify the most convenient HPM geometry and configuration to be fitted into the considered channel, and sizing properly the lateral by-pass chamber;
- improvements in the knowledge available on HPM converters inserted in a real working environment, since only two practical applications of such technology are known to the author up-to-date;
- reduction of the uncertainties existing in input parameters to the economic analysis by gathering information about unit cost of HPM installations from different sources;
- introduction of a new scenario to contemplate the possibility of self-consumption of the produced energy within the WWTP itself avoiding the necessity of establishing grid interconnection and reducing the energy consumption of the plant.

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