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Energy Recovery in Existing Water Networks: Towards Greater Sustainability

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Abstract: Analyses of possible synergies between energy recovery and water management are essential for achieving sustainable improvements in the performance of irrigation water networks. Improving the energy efficiency of water systems by hydraulic energy recovery is becoming an inevitable trend for energy conservation, emissions reduction, and the increase of profit margins as well as for environmental requirements. This paper presents the state of the art of hydraulic energy generation in drinking and irrigation water networks through an extensive review and by analyzing the types of machinery installed, economic and environmental implications of large and small hydropower systems, and how hydropower can be applied in water distribution networks (drinking and irrigation) where energy recovery is not the main objective. Several proposed solutions of energy recovery by using hydraulic machines increase the added value of irrigation water networks, which is an open field that needs to be explored in the near future.

Keywords: irrigation water networks; water-energy nexus; renewable energy; sustainability and efficiency; hydropower solutions; water management

1. Hydropower Generation

Society's energy consumption worldwide has increased by up to 600% over the last century. This increase has been a direct result of population growth since the industrial revolution, in which energy has been provided mainly by fossil fuels. Nevertheless, today and in the near future, renewable energies are expected to be more widely implemented to help maintain sustainable growth and quality of life and, by 2040, to reduce energy consumption down to the 2010 levels [1].

Sustainability must be achieved by using strategies that do not increase the overall carbon footprint, considering all levels of production (macro- and microscale) of the different supplies. These strategies' development has to be univocally linked to new technologies [2]. Special attention must be paid to those new strategies that are related to energy recovery. These new techniques have raised interesting environmental and economic advantages. Therefore, a deep knowledge of the water-energy nexus is crucial for quantifying the potential for energy recovery in any water system [3], and defining performance indicators to evaluate the potential level of energy savings is a key issue for sustainability, environmental, or even management solutions [4].

Energy recovery, with the aim of harnessing the power dissipated by valves (in pressurized flow) or hydraulic jumps (in open channels), is becoming of paramount importance in water distribution networks. Recovery will allow the energy footprint of water (i.e., the energy unit cost needed to satisfy each stage of the water cycle: catchment, pumping, treatment, and distribution) to be reduced, even considering that energy generation is not a priority for these systems [5–7], although this recovery contributes to the development of more sustainable systems. This production could also contribute to the exploitation costs reduction in these systems, increasing the feasibility of drinking and irrigation water exploitation.

Among all of the different types of renewable energy (e.g., photovoltaic, solar thermal, tidal, and wind), the hydropower plant stands out for its feasibility. Historically, large installations can be found in dams around the world to take advantage of the potential energy created by different water levels. The most important hydropower plants are located in countries such as China, the United States, Brazil, and Canada. Currently, China has the greatest installed capacity (exceeding 240 GW), with production greater than 800 TWh in 2012 and an average growth of capacity of 20 GW/year [8]. In Brazil and Canada, hydropower plants represent 84% and 56% of the total energy consumption, respectively. The production of this type of energy in these countries reaches 16% of the total consumed energy [9,10]. Figure 1 shows the technical, economic and exploited potential on each continent.

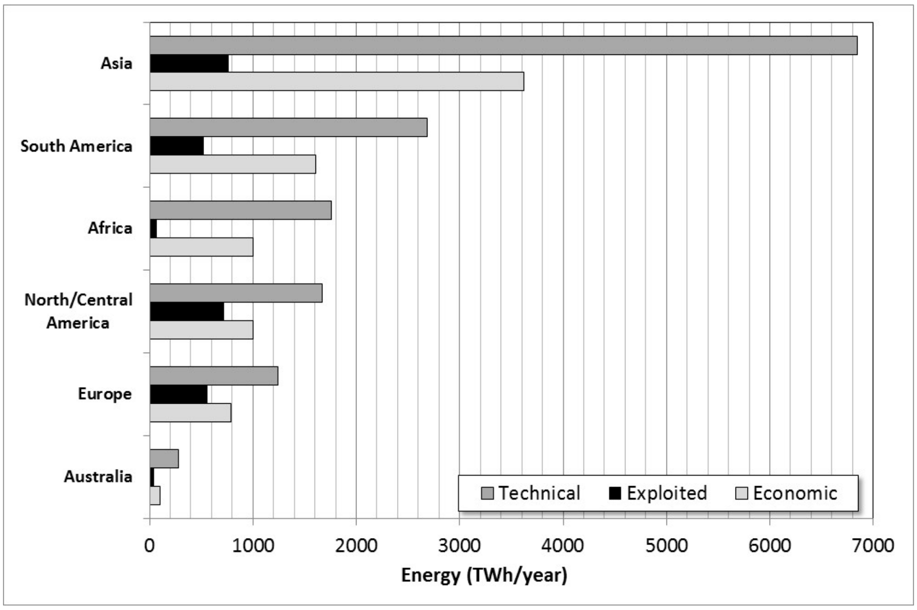

Figure 1. Worldwide hydraulic potential (adapted from [11]).

Going further, Spänhoff [12] performed a worldwide projection of the installed capacity of renewable energy for the United States Energy Information Administration. Hydropower has been the largest renewable source of energy in the period 2004–2010, and it will probably have the highest installed capacity in 2035. According to these forecasts, the installed capacity of hydropower will exceed 1400 GW. This installed capacity will be three times higher than that of wind energy and more than fifteen times greater than that of photovoltaic energy (Figure 2). The actual implementation of these renewable energy systems (solar and wind) in 2016 has been lower than the predicted values (Figure 2). The installed solar capacity is only 30% of the predicted capacity; the wind capacity is only 70% of the predicted value, and the hydropower capacity is approximately the value indicated in Figure 2 [13].

In Europe, renewable energy generation has increased by 96.17% in the period 2002–2013, with production equal to 2232.5 TWh in 2013 [14]. In this decade, the power produced by hydropower plants increased only 16.38%, but other sorts of energy (e.g., solar, wind, and biomass) have experienced greater increases. For instance, in Spain, the increase in renewable energy generation was 152% in this period, but the increase was 73% for Spanish hydropower production.

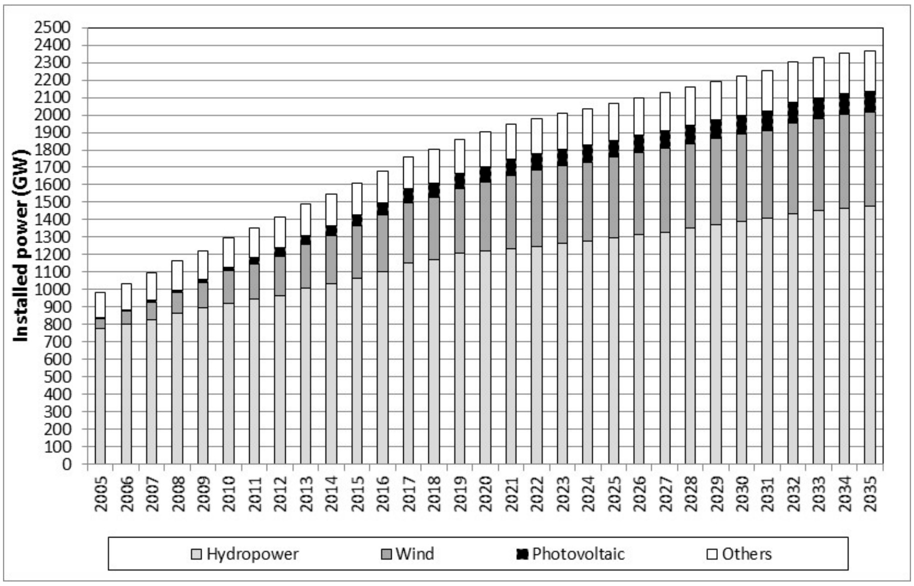

Figure 2. Trends for worldwide renewable energy (adapted from [13]).

Considering all of these renewable energy systems, wind energy has increased by 477%, with a total generation of 53.90 TWh/year. Photovoltaic energy has increased by 4300%, producing 22.85 TWh in 2013 [14]. Nevertheless, the growth of hydropower production has been uneven due to the irregularity of rainfall in the Iberian Peninsula, although the trend is upward [15]. In Spain, the Institute for Energy Diversification and Saving estimated that the untapped generation potential of small hydropower is 1000 MW [16]. Therefore, the development of renewable energy has a promising future, if the potential exploitation is considered. This promising development has positive aspects (e.g., lower environmental impact and generation of stable electrical supply) compared to other renewable energies (e.g., intermittent generation, such as solar or wind) [17]. In addition, this type of energy generation can be very important in the development of multipurpose water systems, where generation is another possible water use [18].

In the near future, part of the growth of hydropower production must come from the retrieval of potential energy embedded in water distribution networks. Considering the potential reduction of natural resources due to extensive agriculture or unsustainable water use on a global level, any investment in energy water recovery is crucial. Therefore, the whole water cycle must be included in the process of energy recovery, including both drinking and irrigation systems. This coupled water-energy nexus will allow the consideration of these systems as a new sustainable and efficient source of energy.

In this framework, the state of the art in the traditional field of hydropower (installed capacity) with a more advanced vision of the energy implications in drinking and irrigation systems is presented, considering the possibility of installing energy recovery in water distribution networks. The objective is to show the hydropower potential in water distribution networks. The installation of these systems will help increase energy efficiency. In the particular case of irrigation, improving the efficiency will allow the reduction of exploitation costs, decreasing pressure on the profit margin, as well as the environmental [19] and economic aspects [20].

2. Energy Recovery in Water Networks

Although there is not a consensus at the European level, the accepted demarcation between large and small hydro by the European Commission is whether the installed power capacity exceeds 10 MW [21]. When the installed capacity is below 100 kW, the generation system is called micro hydropower and when the generated power is below 10 kW, it is called pico hydropower.

2.1. Large Hydropower

Large hydropower in developed (20th century) and developing countries (e.g., China, Brazil, and South Africa) in the early 21st century has been very large, with this generation system providing the main energy source in those countries where topography, hydrology and climatology allow hydropower recovery.

Although China began to develop its hydropower strategic plan in the 1950s, it has quickly overtaken other countries. Its development started with the Liujiaxia dam, which was completed in 1974 and has an installed capacity of 1250 MW. In 2012, China finished the Three Gorges Dam, which has a total installed capacity of over 20,000 MW. A project is currently being developed in the Yarlon Tsagpo Canyon with an installed capacity of over 40,000 MW, double the installed power in the Three Gorges Dam [8]. China has far exceeded the milestone achieved by the Hoover Dam (Colorado River, United States) in 1936, where 2000 MW were installed; or the 12,000 MW installed in the Itaipu Dam (Parana River, Brazil and Paraguay) in 1966, now with 14,000 MW. In Spain, up to 2013, the installed capacity is approximately 18,000 MW, and the hydropower installations do not exceed 400 MW on average.

Ansar [22] made an inventory of the 245 largest hydropower sites in the world (1934–2007). Among them, 72 are located in East Asia, 50 in Latin America, 40 in North America, 29 in Africa, 29 in Europe and 25 in South Asia. Of these, 97 dams are producing electricity, 89 are multipurpose (including hydropower) and 59 are devoted to irrigation and other uses. These plants are occasionally reversible to take advantage of the available volume of water, adjusting the electric energy injected to the grid according to the energy demand. Rehman et al. [10] established that the worldwide installed capacity of reversible plants is 104 GW (presently, the total installed capacity of hydropower is 1000 GW), of which 22.2 GW are installed in North America, 44 GW in Europe (5.3 GW in Spain), 33 GW in Asia, and the remainder in Africa and Russia. These authors refer to efficiencies between 70% and 80%.

Regarding environmental performance indicators of hydropower solutions, these plants have a positive impact on global climate change [23], based on the carbon footprint, which is the parameter used to determine the environmental impact, which has taken on special importance since the 1990s. This parameter is defined as the sum of the greenhouse gases emitted by an organization, event or product, expressed in terms of CO_2 equivalent units (CO_2-e) [24]. According to Zhang and Xu [25], the influence of the carbon footprint depends on many factors, most importantly the construction and maintenance costs (because these represent more than 60% in earthen dams and 50% in concrete dams) [9]. The range of emissions for these systems is between 2 and 240 gCO_2-e/kWh [9,26], with the carbon footprint in hydropower plants being smaller than that in coal plants. These non-renewable energy plants have emissions above 890 gCO_2-e/kWh [26–28]. Considering these emissions, hydropower plants saved 3.3 billion tons of CO_2 emissions in 2014 and will help reduce emissions by over 120 billion tons between 2015 and 2050 [13] compared to coal plants.

Regarding the economic aspects of large hydropower, the investment ratio (€/kW) decreases as the installed capacity increases, reaching values from 2170 to 470 €/kW for power ranges between 200 and 1400 MW [29,30]. Civil works represent between 70% and 80% of the total investment, and the remaining costs are devoted to electro-mechanics and hydraulic equipment [10].

2.2. Small Hydropower

The expansion of these installations was due to the development of the Francis turbine (for medium heads) [31], contributing both to the reduction of greenhouse gases and to the establishment of electrical service in remote rural areas or consumption points located away from supply points. This "social contribution" should be taken into account in viability studies in developing countries. As in large hydropower, the leading countries in small hydropower energy are China, Brazil, India, Canada, and some European countries. In 2013, China had a total installed capacity above 80 GW, which supplied more than 650 rural areas [8], with a range of installed power between 0.5 and 10 MW in each plant [32]. Brazil had 397 power plants in operation in 2011, with an installed capacity of

3.5 GW. Currently, the potential capacity is equal to 25.9 GW [33]. The United States Department of Energy tabulated more than a half million sites, with an installed potential of 100 GW [34], representing 10% of the current generation in the United States.

Currently, Australia has 60 small hydropower plants with a total installed capacity of 0.15 GW, which is 10% of the potential capacity. Australian Administration has projected three new plants with an installed capacity of 20, 8.4, and 7 MW, which will be developed in the future [35]. In India, the potential capacity is 15 GW, of which 2.4 GW are currently installed in 674 plants, with an expected increase of 9.4 GW in 2017 [36]. Ushiyama [37] established an installed power capacity of 30 GW for Japan in 2010, where small hydropower was practically non-existent. However, Japan has already started to develop projects in remote areas with a rate of capacity installation greater than 300 MW per year, with an installed power and potential capacity in the near future of 3.52 and 6.82 GW, respectively [38]. Across the African continent, small hydropower is also being developed in rural zones, where these plants are generating significant social benefits with a lower installed capacity of 300 kW [39].

According to the European Small Hydropower Association (ESHA), the total installed capacity in 2005 was 12.4 GW, of which six European Union members (Italy, France, Spain, Germany, Austria, and Sweden) in addition to Switzerland and Norway possess more than 90% of the installed capacity [40]. Alonso-Tristán et al. [41] presented the distribution of the small hydropower installed in Spain using data from Red Eléctrica de España (REE). This country represented 23.1% of the hydropower generation in European small hydropower in 2008 [42]. The potential growth in installed power capacity is 10 GW, with an annual production above 38,000 GWh [30], and the installed power will reach 17.3 GW (an increment of 39.51%) [41] in the period 2005–2020, as depicted in Figure 3.

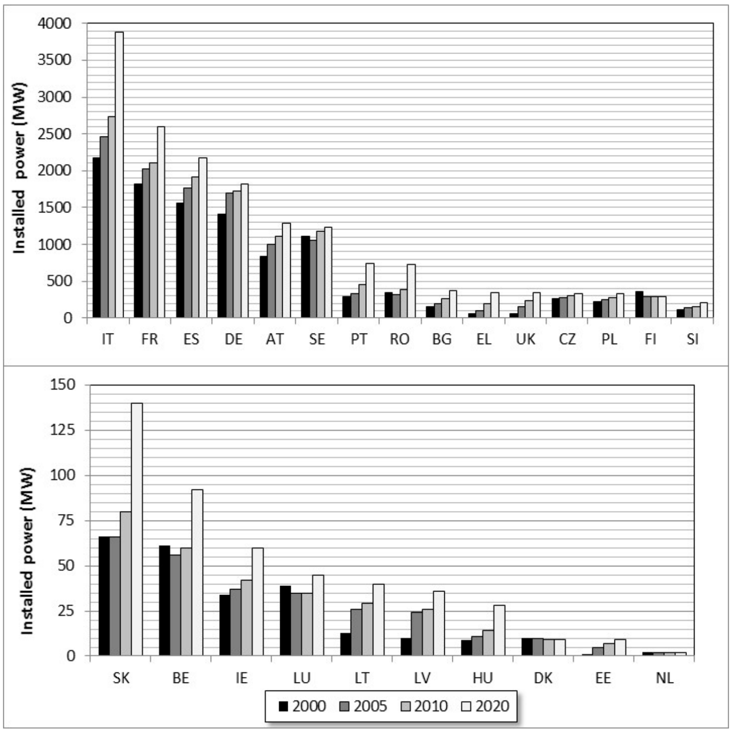

Figure 3. Planned installation of small hydropower capacity in 2005–2020 by European Union countries (adapted from [40]).

Small hydropower has several advantages: less negative impacts than large hydropower and available potential to increase renewable energy production. ESHA estimated an annual reduction of 29×10^6 tonnes of CO_2 as a result of the 13 GW installed capacity in Europe [43]. Amponsah et al. [44]

analyzed different values of the carbon footprint of small hydropower and established a range between 2 and 74.9 gCO_2-e/kWh based on the installation and the type of plant. In the particular case of micro-hydropower, Gallagher et al. [45] analyzed the carbon footprint of three plants with installed capacities of 15, 90 and 140 kW. The results of this analysis were 2.14, 4.39, and 2.78 gCO_2-e/kWh, respectively. These values emphasize the positive environmental impact of hydropower solutions.

Regarding economic aspects, Kosnik [34] developed an economic analysis based on several small plants, obtaining a non-linear relationship between the cost of implementation and installed power (small, micro or pico). Ogayar and Vidal [46] also analyzed the distribution of costs for small hydropower, which are distributed among civil work (40%), turbine (30%), electro-mechanical and regulation equipment (22%), and construction management (8%). This type of renewable energy project is viable when the required investment is below 2000 $/kW [47], although special attention should be paid to the environmental and social benefits provided by these installations. At the European level, according to the General Direction for Environment, the average cost of investment for plants with an installed capacity below 10 MW is between 2941 and 4072 €/kW, depending on the characteristics of the system (e.g., flow, head, orography) [40]. Mishra et al. [48] proposed formulas that use the turbine, installed power capacity, and net head to estimate the required investment. These expressions can be used to determine the associated costs.

Finally, the classification of these installations is referenced in European legislation [47] according to the installed power. However, other classifications have been proposed that depend on the type of plant from an operational point of view [16,49,50].

(1) Power plant in flow or run-of-river: This system has no regulation reservoir and only takes advantage of the hydraulic head when the flow circulates. In mountain areas, with medium heads, the flow is diverted through a weir and a penstock carries the flow to the power house. If the topography does not allow it, the hydraulic head must be created by building a higher dam.
(2) Power plant at the foot of a dam: The flow is regulated by a reservoir. In the case of small hydropower, reservoirs or dams are used to ensure project viability.
(3) Power plant in water distribution network: The distribution network is used to take advantage of available pressure or kinetic energy, depending on the system characteristics.

2.3. Type of Hydraulic Machines

Hydraulic machines are classified according to the system (pressurized or open channels) in which they are installed (Figure 4). In open channels, all types of hydraulic wheels have been traditionally used to take advantage of waterfalls. According to the type of energy used (potential, pressure, or kinetic), the machines are classified as gravitational, hydrostatic, or kinetic. Gravitational machines take advantage of different water levels to extract energy from the flow (e.g., Archimedes screw or waterwheel). Hydrostatic machines operate by the difference of hydrostatic pressures on both faces of a blade (e.g., hydrostatic pressure wheel). Finally, if a wheel uses the velocity of the flow to move the axis of the machine, this type of machine is called a kinetic machine. There are many different types of kinetic machines (e.g., helical turbine with vertical or horizontal axis, overshot wheel, and ducted turbine) [51].

In pressurized water systems, the most frequently used machines can be grouped into traditional machines (which are categorized as action and reaction machines) and adapted machines. The last group includes hydraulic machines that normally work not as turbines but as pumps. In reaction machines, the hydraulic power is transmitted to the axis of the machine by varying the pressure flow between the inlet and outlet of the impeller, which depends on the specific speed of the machine (e.g., Francis and Kaplan). In action turbines, the energy exchange (hydraulic to mechanical) is carried out at atmospheric pressure, and the hydraulic power is due to kinetic energy of the flow (e.g., Pelton and Turgo).

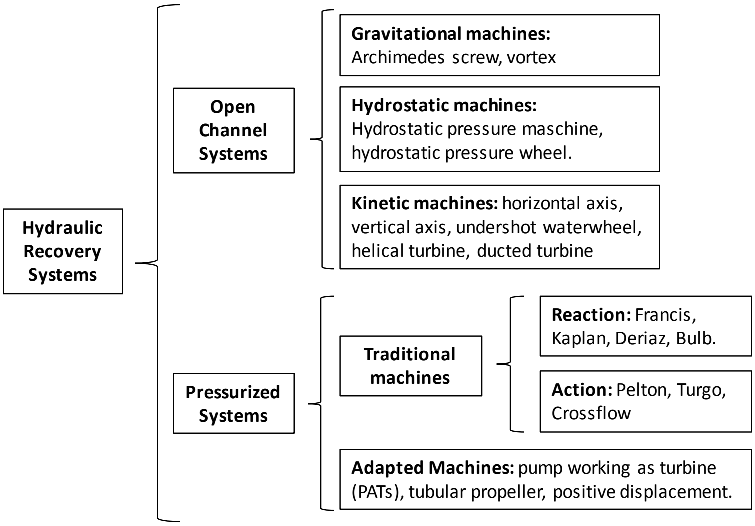

Figure 4. Classification of hydraulic machines.

These types of machines are used in large and small hydropower, depending on the nominal flow and the available head (Figure 5).

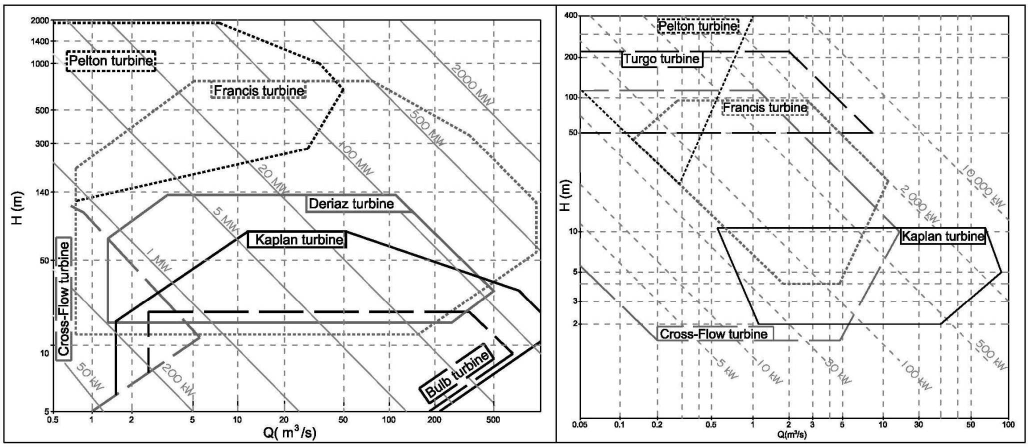

Figure 5. Selection of turbine depending on head and flow in: large (**left**); and small (**right**) hydropower [16,31].

Currently, most of the turbines installed for large hydropower are Pelton, Francis, Kaplan, or Deriaz turbines [31]. These turbines present different performance curves, which depend on their specific speed and discharge number [21,52]. Gordon [53] analyzed both the efficiency of 107 turbines that had been installed since 1908 and the increase in efficiency obtained with replacement impellers in 22 power plants, evaluating the improvement in the performance of propellers over time. Increases in the performance of the machines were obtained, rising from efficiencies lower than 50% in 1920 to above 96% in some current cases.

Regarding hydraulic machines installed for small hydropower, Paish [47] established the efficiency of these machines according to the type and head ratio. The efficiency has values of approximately 90% for Pelton turbines over a wide head ratio (0.2–0.8). In crossflow turbines, the values of efficiency are close to 80% for a head ratio (0.2–1). Francis and propeller turbines present efficiencies of approximately 85% for a head ratio (0.9–1).

The development and improvement of large and small hydropower systems have allowed the adaptation of the machines to water distribution networks, establishing the group called "adapted machines" (Figure 4). This group of machines is used in micro and pico hydropower plants. Pump as turbine (PAT) [54], tubular propeller [55], and positive displacement machine [56] are included in this group (Figure 6).

Figure 6. Hydraulic machines at IST-Universidade de Lisboa: PAT (**left**); and tubular propeller (**right**).

This group of machines can be installed in places where energy is currently dissipated for specific flow and pressure operating conditions. These conditions mainly depend on user demand and the minimum pressure required (when the machine is installed in a pressurized water network). The existing demand establishes the circulating flow over time in the line, whereas a required pressure establishes the maximum recovered head. In pressurized water networks, the excess of energy is dissipated with pressure reduction valves. In open channel flows, this dissipation of energy is carried out by means of hydraulic jumps. In micro and pico systems, conventional machines can be installed according to installed power and head characteristics (e.g., micro Francis, Pelton, Turgo, and Cross-Flow), but the high investment cost makes the installation not viable.

In 1931, Thoma [54] implemented the first pump working as a turbine (PAT). Later, other authors presented more research that presented the description, operation, performance, and theoretical model of these machines [57–64]. PATs are normally used in pressurized water networks but they can also be used in open channel flows when complementary civil works are carried out to adapt to PAT operating conditions. These machines present a high range of flow and head for installation according to the typology of the machine (Figure 7). The best efficiencies vary between 40% and 70% as a function of the specific speed [58].

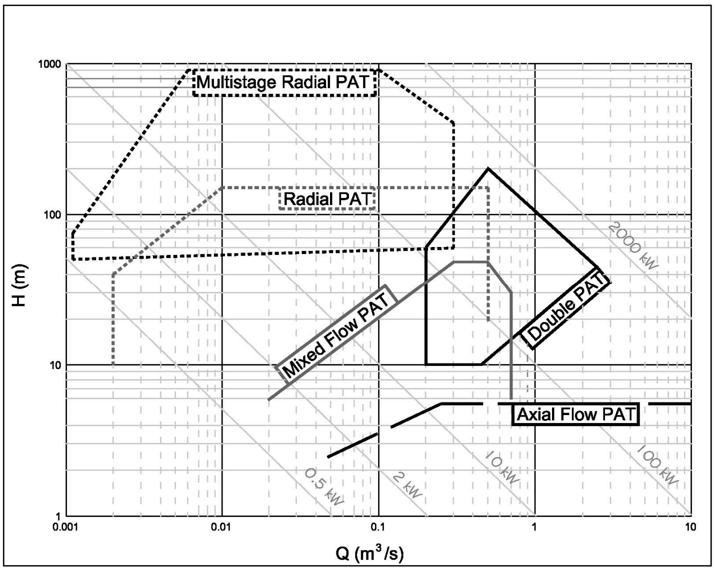

Figure 7. Range of application of PATs (adapted from [54]).

PATs become the technological solution to efficiently recover energy in water distribution networks. The main advantage of these machines is their immediate availability for installation and lower cost compared with conventional machines. Nourbakhsh and Jahangiri [65] established that the payback period of these machines is less than two years for installed capacities between 5 and 500 kW. These payback values make micro generation in water distribution networks feasible.

Elbatran et al. [64] listed the advantages of these machines in micro hydropower plants, such as a 50% reduction in the cost of the machine compared to a conventional turbine; the existence of a large availability of operating ranges depending on the hydraulic head and flow; simple management and operation; and a lifespan of twenty-five years. Furthermore, they have lower installation costs, which can improve the viability of small projects [60].

3. Micro and Pico Hydropower Solutions

3.1. Energy Recovery in Open Channel Networks

Micro hydropower can use different hydraulic heads or diversion schemes in small dams in rivers and ravines, in open irrigation channels and in drainage systems. Some examples of these systems can be found in several regions, such as the western part of the Himalayas [66], Bangladesh [67], Nigeria [68], Laos [69], Europe [41], or Lithuania [70]. Although it might seem that the development of these hydropower plants has been recent, this is not true because watermills were present in all continents many years ago, were fundamental to moving other machines in the Industrial Revolution, and can still be found operating in some countries (e.g., United Kingdom, France, Spain, USA, Africa, and part of Asia) [71,72]. This technology is currently essential to generate electrical energy in rural areas and to support the social and economic development of these isolated regions.

Water wheels can also be used in other open channel flows. For example, these solutions can be located in water treatment plants. These elements can also be installed in urban infrastructure, where energy recovery systems are established to reduce the energy footprint of urban water systems [73]. In these facilities, Ramos et al. [28] proposed the use of an urban storm-water drainage system to take advantage of storm retention ponds and to develop energy recovery systems using the rain storage volume. This solution contributes a new source of clean energy, which is involved with the water drainage system. An example of energy recovery is analyzed by Novara et al. [74] in a wastewater treatment plant in the city of Asti (Italy). The flow in this channel oscillates between 0.07 and 0.83 m^3/s, while the available head changes between 0.062 and 0.744 m. With these values, a hydrostatic pressure machine (HPM) is proposed to be installed. This wheel is an experimental waterwheel specifically designed for application in open channels with reduced head, developed and improved by Senior et al. [75], patented by Austrian inventor Adolf Brinnich, and tested under the HYLOW project as part of EU's Seventh Framework Program between 2008 and 2013 [76]. If the energy balance is carried out, the maximum electrical power is approximately 650 W with a flow equal to 0.29 m^3/s, for a daily power of 10.9 kWh. In these conditions, 48% of the hydrostatic energy is converted into electrical power, 40% is mechanical loss, and 12% is electrical loss in the generator and transmission.

Similarly, in open channel irrigation systems, energy recovery can also be implemented by installed turbines in small dams or irrigation reservoirs [77,78]. An example of these installations is the analysis made by Butera and Balestra [79], who determined the potential generation by hydropower plants for the Piedmont region (Italy). This region has an installed capacity of 46 MW, of which 45% is pico hydropower, 49% is micro and 6% is small, with an average hydraulic potential of 1.5–2 kW/ha. Tarragó et al. [26] developed a preliminary study in the Alqueva's irrigation system, where twenty-two hydrostatic pressure machines were studied in different locations with hydraulic heads below three meters. Using this assumption, the theoretical energy recovery reached 406.64 MWh/year in 67,932 ha of this region.

3.2. Energy Recovery Water Pipe and Irrigation Systems

Currently, energy recovery in pressurized water distribution networks (both urban or irrigation water supply) has great significance. Relative to urban supply systems, the energy consumption in water supply networks represents 7% of the world's consumption of energy [80]. Water distribution involves an energy footprint between 0.18 and 0.32 kWh/m^3, according to the California Energy Commission [81]. In addition to energy consumption, energy analysis of these networks has shown that an increase of pressure is correlated with increased leakage [82]. This problem justifies the installation of pressure reduction valves (PRVs) in many water distribution networks. These valves reduce pressure and, therefore, leakage volume. This directly proportional correlation between leakage and pressure caused the pioneering study of alternatives to leverage the dissipated energy by PRVs in water supply systems [57]. An unconventional solution was considered: replacing PRVs by PATs [57,59]. Ferracota et al. [60] studied leakage reduction. They presented and integrated a new technical solution with economic and system flexibility benefits, replacing pressure reduction valves by pumps used as turbines (PATs). The optimal operating point of the PATs was selected by using a variable operating strategy. Carraveta et al. [63] established a PAT operating scheme with a PRV in parallel. This operating scheme and the variability of flows over time in network pipelines due to user demand have fostered leading studies to develop variable operating strategies in these machines. These strategies allow the variation of the rotational speed of the hydraulic machine [83,84]. Ferracota et al. [85] have begun studies to improve efficiency prediction in the machine through experimental tests in semi-axial machines when the rotational speed varies. Preliminary studies in drinking water systems have been developed through computational simulations [59,60,86]. These studies considered average flows or hourly uniform patterns in all consumption joints for the development of simulations of water supply networks [87,88]. These energy recovery studies have promoted the use of water supply networks to generate clean energy, using the dissipated energy in PRVs [89]. These studies have resulted in some pilot installations emerging for evaluation (e.g., Murcia (Spain) [90], Portland (Oregon) [91], Hong Kong [89], and Kildare (Ireland) [92]).

In addition to water supply systems, water irrigation networks are very important for the improvement of energy efficiency in the water cycle. Worldwide water consumption is 3925 km^3/year [93], which is distributed such that 69.53% of water is used for irrigation, 18.70% is used for industry, and 11.77% is used for drinking water systems. In Spain, water consumption is distributed as follows: 80% for irrigation, 15% for drinking, and 5% for industry. The annual volume used for agriculture equals 16,344 hm^3 [94].

Hence, because the volume of water consumed for irrigation is higher than in urban systems, the modernization of irrigation should not only be associated with high technology and automation but also with water management that accounts for the sustainability of this infrastructure. The study of the installation of micro and pico hydropower is necessary because the irrigated surface area is huge (approximately 324 million hectares in the world are provided with irrigation installations, of which 86% are gravity irrigation, 11% sprinkler irrigation and 3% drip irrigation [95]). In Spanish economic terms, the irrigation water distribution cost was €1285 million in 2012. This value represents 20% of the total cost of the water supply service in Spain [96], considering that the irrigated surface area in Spain is 3.54 million hectares (1.09% of the worldwide irrigated surface area) [97].

Therefore, if the annual volume of water consumed in irrigation networks worldwide is measured, the development of systems to reduce the energy consumption is of the utmost importance. These new solutions should also try to improve, as much as possible, the environmental and economic sustainability of irrigation, considering that the modernization of irrigation water systems introduces an average increase of installed power equal to 2 kW/ha [98].

3.3. Strategies for Sustainability and Energy Efficiency in Pressurized Water Networks

3.3.1. Pumped Water Systems

Pumped water systems have been analyzed by different authors [99–103] whose main objective has been to minimize the energy costs. Rodriguez-Diaz et al. [99] proposed a new methodology with energy savings between 10% and 30% in real case studies, considering the most critical consumption points, which depend on needs and location. Moreno et al. [100] developed a methodology in which characteristic and efficiency curves are optimized depending on the recorded flows, obtaining a 32.33% average reduction of installed power in the studied networks.

In other research, energy reduction has been carried out using strategies to minimize energy consumption through optimal operating schedules, reducing energy footprints by 36.4% [101,102]. Costa et al. [103] presented a general optimization routine integrated with EPANET [104]. This routine allows the determination of strategic optimal rules of operation for any type of water distribution system. Cabrera et al. [105] developed a methodology to carry out an energy audit, which detects weaknesses in pressurized water networks. This methodology is applied in a real case, obtaining energy savings above 40%. In all of the cited cases, energy savings correspond to an economic reduction between 35% and 50% of the energy costs. Ferracota et al. [60] integrated a new technical solution with economic and system flexibility benefits, which replaces pressure reduction valves by pumps as turbines. In the majority of methods, when energy optimization is carried out in pumped water systems, the objective is easily defined as minimizing the energy consumption, with the solution being the establishment of optimized irrigation schedules according to the minimum necessary pressure and irrigation needs at each consumption point.

3.3.2. Gravity Water Systems

If an irrigation network is a gravity system, the best solution is not to convert an on-demand water irrigation into a scheduled network because this decision can irritate farmers, and reduce their operational freedom. Therefore, if a water manager wants to increase the system sustainability and energy efficiency of a network by the installation of energy recovery systems, the manager should know the flow distribution over time. The analysis of water distribution systems allows the establishment of some crucial aspects of the recovery system, such as the type of hydraulic machine, the best efficiency point (BEP) and the range of operating conditions for the energy converters [64].

Preliminary values of recoverable energy have been obtained using average circulating flows for both irrigation [26] and water supply networks [106] in some studies. The authors have used daily patterns in these studies. To analyze the variation of flows over time, Pérez-Sánchez et al. [107] developed a new methodology to estimate the hourly circulating flows in any line based on the opening probability of the irrigation points, which depends on farmers' habits (i.e., irrigation duration, maximum days between irrigation, weekly irrigation trend, and irrigation start). This methodology can also be used in water supply networks when behavioral patterns are known. These demand patterns allow the water network to be simulated and the energy balance to be calculated to determine the percentage of energy dissipated by friction losses, the energy necessary for irrigation, the non-recoverable energy, and the theoretically available energy. In the case of Vallada (Spain) [107], the energy dissipated by friction is approximately 4.10% of the provided energy (with a maximum energy footprint of 2.85 $\mathrm{kWh/m^3}$), with the theoretical recoverable energy in the network equal to 68.70%, when all of the irrigation points are considered elective places of recovery.

The feasibility of an energy project is not guaranteed when a high number of machines is installed in the network; thus, an analysis of the water network is needed to maximize the energy recovery. Samora et al. [108] developed a methodology that uses simulated annealing to maximize recovered energy in a water supply network [109]. This methodology selects the lines depending on the recovered energy, and considering the feasibility of the facilities according to an economic criterion. For these preliminary studies of feasibility, Castro [16] proposed a simple economic balance where the payback period is only determined through the investment cost, incomes and maintenance cost, which depend on the installed power. In an advanced or existing project, other more complex and detailed methods can be used, which consider the annual interest and the inflation rate [110,111].

Therefore, if the feasibility is studied, knowledge of the performance and head curves as functions of the flow in the selected machine is necessary to determine the real recovered energy. The proposed PAT curves by Rawal and Kshirsagar [112] and Singh [113] (Figure 8) can be used in the analysis to help select a PAT. These curves allow the impellers' diameter to be selected as a function of the specific rotational speed (ns), the discharge number (ϕ), and the head number (ψ). These parameters are defined by Equations (1)–(3) [24]:

$$ns = N\frac{\sqrt{P_R}}{H_R^{1.25}} \tag{1}$$

$$\phi = \frac{Q}{ND^3}\ (\text{discharge number}) \tag{2}$$

$$\psi = \frac{H}{N^2D^2}\ (\text{head number}) \tag{3}$$

where N is the rotational speed (rpm); P_R is the rated power (kW); R is the pump design point or the best efficiency condition; H_R is the rated head (m w.c.); Q is the circulating flow (m^3/s); H is the recovered head of the machine (m w.c.); and D is the impeller diameter (m).

If the previous premises are used, different studies have been developed in water systems (irrigation and drinking networks), considering strategies to maximize the energy efficiency. In the particular case study of Vallada (Spain) [107], where the annual water consumption is 930,000 m^3/year, the actual recovered energy is 26.51 MWh/year. This recovery represents 9.55% of the energy provided to the network, with a simple payback period of 5.28. In a preliminary study of Alqueva (Portugal) [26], the theoretical energy recovery is at least 2.12 MWh/year in 68 ha of pressurized irrigation, for a water consumption of 179,000 m^3/year.

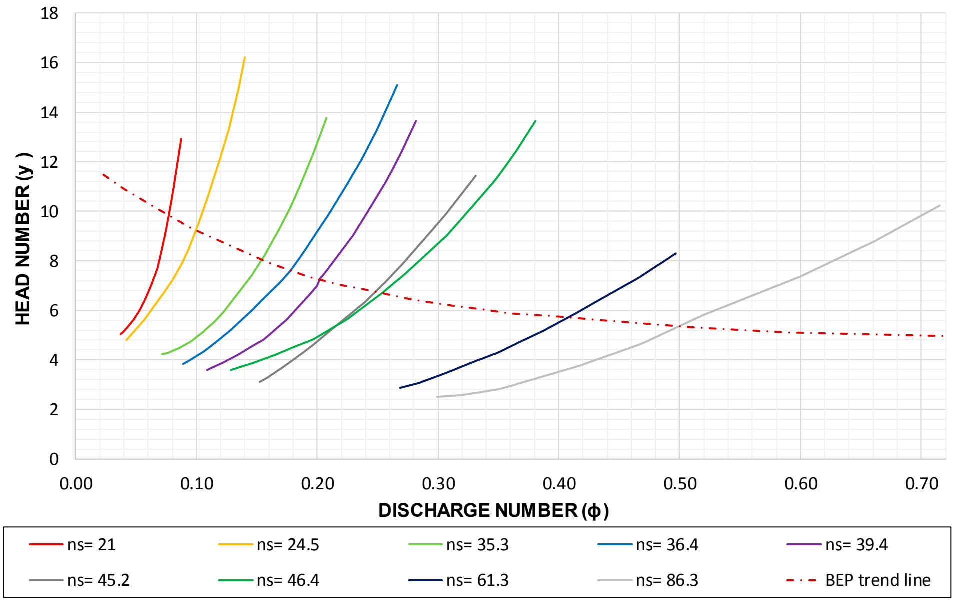

Figure 8. Head number depending on the discharge number (adapted from [112,113]).

In water supply systems, a case study of Lausanne (Switzerland) [106] finds that the real recovered energy represents up to 5% of the available energy. In a case study of Fribourg in the same country, the recovered energy reaches 10% of the available energy [114]. Another energy study developed in collaboration with the Consortium of Commons for the Monferrato Aqueduct (Italy) [74] determines an energy recovery equal to 9585 kWh/year when the pressure reducing valve is replaced by a PAT with a constant flow of 7 L/s and head of 75 m w.c. These examples show the importance of this type of solution for economic and environmental sustainability in water systems, if similar solutions are implemented.

From the economic point of view, the benefits of selling energy and generating income can be quite significant in some cases (although this generation is irregular over time because it depends on the flow, which varies as a function of consumption in water networks). Some particular analyses of these systems (and, more specifically, of PATs) present payback periods less than five years, with an installed capacity between 5 and 500 kW [8]. However, the importance of these solutions consists in the generation of energy for self-consumption by the local communities, i.e., for extracting water from their own water wells, electric supply in irrigation communities, or individual use at the irrigation points, avoiding investment in the electric grid.

From the environmental point of view, the use of these renewable energy sources reduces the emission of greenhouse gases when they are compared with non-renewable energy (e.g., fuel, usually used in electric generators installed in irrigation communities or irrigation points). Therefore, these recovery systems can supply the users' demand for low energy consumption in their facilities. Regarding the environmental added value, the theoretical reduction of CO_2 emission is 216.2 t/year in Vallada's network.

The development of studies to install energy recovery in pressurized water networks (mainly in supply systems) has been important, as previously discussed. The development of these studies has focused on the use of non-conventional hydraulic machines to generate energy and on energy analyses using different installation schemes for these machines. Table 1 summarizes the current development of small energy recovery in pressurized water supply networks.

Table 1. Analyzed topics related to recovery systems in water supply networks.

Analyzed Topic	References
First PAT	[54]
Reduction of leaks, decreasing the pressure in water supply systems and increasing the efficiency	[57,60,80,82,84,87]
Proposal to use adapted machines (PATs and tubular propeller) in water supply systems to reduce the pressure	[55,57]
Description and operation of a PAT with a review of available technologies	[56,64,67,75,76]
Performance and modeling PAT	[56,58,61,65,85]
Installation of recovery systems in water supply networks	[59,79]
Implementation of simulations to determine the theoretical recovered energy in water supply and irrigation systems	[26,74,77,86,106–108]
Design of variable operating strategies to maximize the recovered energy	[59,60,62,84]
Economic cost of implementing recovery systems in water supply and irrigation networks	[8,16,64,84]
Environmental advantages	[66,78,88]
Policies and analyses to help the development of rural areas	[41,58,68–72]
Pilot plants built in water supply networks	[89–92]
Optimization to maximize recovered energy in water supply systems	[106]

Table 1 shows different topics related to PATs that have been studied by different authors. The description, operating mode, characteristic curves (theoretical and experimental), and simulations (for hourly uniform patterns in all consumption joints) of PATs have been developed, enumerating the advantages (such as good efficiency values and low price) and limitations. The main limitations are lower efficiency when the system operates with oscillating flows and the irregular generation of energy due to variable flow, which hinders both sale and self-consumption.

The development of different research is necessary to solve the previously cited limitations. Future work should focus on obtaining better knowledge of recorded flows over time in any line; improving the variable operating strategies to adapt the rotational speed of machines in each time step; and developing sustainable and feasible electric systems (grid connection or stand-alone operation). These electric systems will increase the viability of selling the energy to the national grid or using it for self-consumption.

4. Conclusions

There are several related scales for the management of the hydraulic energy generation, including local, regional, national and international, when considering water as a resource. However, even today, energy recovery is a very attractive possibility in water networks, with small additional costs for managers and investors. The success of this novel use depends on the experience acquired in hydropower plants with higher installed power.

A deep review has been presented, analyzing the different alternatives for hydropower production from large to pico facilities, according to the production levels, the economic and the environmental points of view, as well as the classification of the hydraulic machines. Considering the evolution of these energy solutions, energy recovery in water distribution networks is an alternative for the development of systems towards more sustainable and efficient solutions. Technological, economic and environmental implications of hydropower systems for energy recovery around the world have to be considered. Despite the large list of references, only a few can be related to agricultural water network energy recovery because this subject has not yet been explored.

Analysis of the references cited in this document establishes that recovery systems in pressurized water networks are:

(1) Recovery systems with less installed power, called mini and pico hydropower plants. These energy recovery systems appeared due to the need to replace waste or non-renewable energy devices with renewable energy solutions. The building of large hydropower plants has been maximized in different developed countries and the development of new large hydropower plants is currently limited due to environmental and social factors. However, the experience in these facilities (i.e., large and small hydropower) has contributed to the development of new recovery systems in pressurized water networks. The most important transfer has been advances in possible recovery machines and improvement in the efficiency of impellers and in water pipe systems as a whole.

(2) The description of machines used in different hydropower plants (i.e., pressurized and open channel flows) has shown that on the one hand, classical machines cannot directly be used or scaled to pico hydropower plants because the adaptation of flow and head presents some difficulties in terms of viability. In contrast, similar or adapted machines can be developed based on classical machines (e.g., Francis turbine vs. radial and mixed PATs; axial turbine vs. tubular propeller or axial PATs). The development of new adapted machines and improvement in the efficiency of the current ones are fundamental challenges for increasing the installation of recovery energy systems in water pipe networks in the near future.

(3) For energy recovery in pico hydropower plants, the PAT is currently the most successful machine to be adapted to these systems, according to previous studies and installed pilot plants. The main positive aspects of these machines are that: (i) the installation of a PAT allows the replacement of a PRV to dissipate excess flow energy; (ii) the PATs′ efficiency values vary between 0.40 and 0.70, operating in reverse mode; (iii) theoretical studies can be developed with the current technology (e.g., computational fluid dynamics (CFD)) based on the classical theory of hydraulic machines (i.e., Euler′s Theorem), for comparison with existing experimental tests; and (iv) they have low investment costs and a high number of available machines. These advantages allow the

installation of these machines in water pipe systems to be promoted. The main aspects negative of PATs are related to their low efficiency when operating outside their best efficiency point. Operation with different flows can be solved by the development of new regulation techniques (e.g., variable operation strategies (VOS)) with electronic regulation. The positive resolution of this aspect is a crucial point for expanding use of PATs in water distribution networks. Issues related to the use of the generated energy for self-consumption may include storage in batteries and integrating this renewable energy in a similar manner as other supplementary sources (e.g., solar and wind).

(4) Different case studies have been developed using specific software (e.g., EPANET and WaterGEMS), which have been combined with optimization methodologies to maximize the recovered energy. Future simulations should take into account the integration of VOS as well as the variation of the machine efficiency with the rotational speed. These simulations should consider discretized demand over time to improve the analyzed energy values because the majority of studies only consider the mean demand value or modulation curves. The development of a specific methodology to determine this variation of flow over time in water supply networks is crucial to improve the fit between theoretical and real values of recovered energy. Regarding the software used, it is necessary to implement operation rules for these machines in specific algorithms. This implementation is the key point in the development of optimized techniques, making possible studies similar to those with water pump systems. The primary need is for correct machine selection and establishment of the rotational speed as a function of the flow, maintaining the maximum efficiency at each operation point of the machine.

Therefore, hydraulic recovery in water networks is a real and necessary alternative to improve the energy efficiency of the whole system. By means of implementing energy converters, the energy efficiency will be increased and operating costs will be reduced (i.e., the energy footprint of water). The implementation of these systems will essentially depend on the physical characteristics of the systems. The orography, topology, and volumes of water consumed establish the economic viability of these recovery strategies in water distribution networks. When the investment analyses are developed, recovery systems have acceptable values of economic feasibility indexes (e.g., payback value and internal rate of return). A better understanding of the operation of each recovery system in terms of water-energy management is needed that considers the high global volume distributed in pressurized water networks (i.e., drinking and irrigation) each year. This understanding will positively contribute to the sustainability and efficiency of near future recovery system applications.

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