

Article

Hydropower Technology for Sustainable Energy Generation in Wastewater Systems: Learning from the Experience

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Abstract: Hydropower is a well-known technology, applied worldwide for electricity generation from renewable sources. Within the current framework, some studies have started to consider its application to existing urban water systems, to harness an excess of energy that otherwise would be wasted. This research sought to determine a methodology to assess the potential of hydropower application to wastewater treatment plants (WWTPs), regarding different aspects of sustainability. Firstly, previously developed methodologies for potential assessment in this sector at a country level were analyzed. Secondly, data from existing real case studies were gathered from publicly available documents and a theoretical analysis of their actual performance was conducted to validate assumptions made in the previous methodologies. As a result, the proposed new approach suggests adapting methodologies for potential assessment at a lower level, considering possible driving factors, other than economic feasibility. To define the study area, the management model scope should be considered. The power to determine the cut-off point for a WWTP to be considered as a potential site, is proposed to be lowered according to technical feasibility. Additionally, bearing in mind the sustainability concept, social or environmental factors should also be introduced in the methodology, tailored to the region being assessed. This novel perspective could provide a closer approach to the most likely decision-making level for these kinds of strategies in the wastewater industry.

Keywords: energy recovery; hydraulic machinery; hydropower; potential assessment; real application; wastewater management; wastewater treatment plants



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1. Introduction

The United Nations 17 Sustainable Development Goals (SDGs) establish a universal agenda to call for action and achieve sustainability in essential aspects of human life, such as hunger or health [1,2]. One of them is SDG 6 'Clean water and sanitation', which includes targets that are also critical for achieving other SDGs [1,3]. At the same time, some SDGs demand actions to preserve natural resources, provide affordable and clean energy and tackle climate change [2]. Although the UN annual climate summits (known as Conference of the Parties or COPs) started almost 3 decades ago, tackling climate change has become a global priority in most recent years, particularly since the Paris Agreement (COP21) in 2015. Under this Agreement countries are being asked to significantly reduce their greenhouse gas (GHG) emissions by 2030 aiming at net zero carbon emissions by 2050 and the results from COP26 this year will be decisive to start making this Agreement operational. To achieve these goals, countries will be encouraged to implement several strategies, including investments in renewable energy generation technologies [2].

Therefore, sustainable management of water networks and treatment facilities is becoming a crucial issue for policy makers, as the needs are expected to soar in the near future [4]. Water should not be regarded just as a consumer product, but as a valuable resource that must be protected, a social responsibility [5]. As such, opportunities to improve wastewater management should not be neglected [4,6].

The primary purpose of wastewater treatment plants (WWTPs) is purifying collected sewage, to achieve an effluent that can be safely discharged into receiving water bodies [7,8]. As an essential service, these facilities deserve to be provided with the best available technologies to protect the environment, with affordable solutions to do so in a sustainable way [4]. This implies obtaining a high-quality effluent as a first goal, whilst simultaneously optimizing the use of other resources [9,10]. Since the electricity demand in wastewater treatment is usually very high [10,11], actions are needed to deal with this environmental aspect including both efficiency improvement and renewable energy generation [12,13]. Figure 1 summarizes the global water cycle with main energy flows.

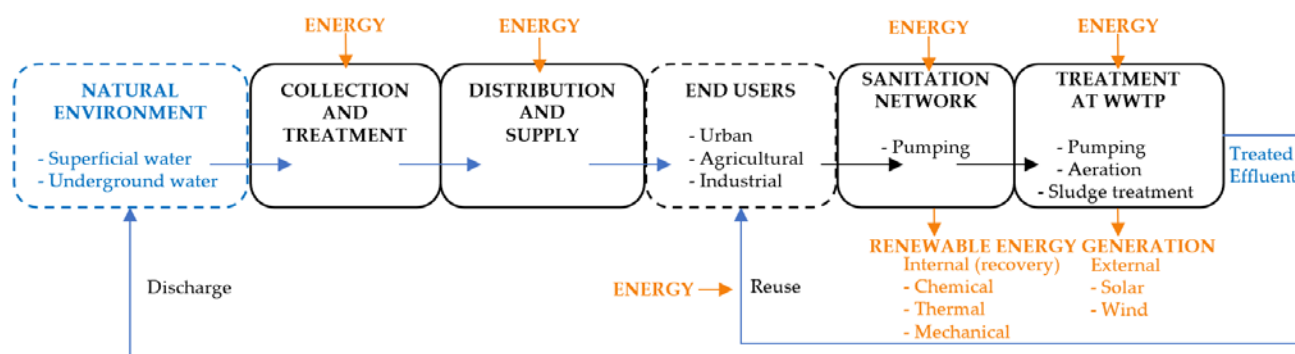


Figure 1. Water cycle diagram.

Concerning renewable energies, generation from biogas is usually the main option considered for WWTPs [14–16]. Biogas production certainly is a very profitable technology for this industry [17–19] and ongoing research is continuously improving its performance and possibilities [20–22]. Nevertheless, the still high complexity of the anaerobic processes required to generate biogas usually limits their application only to the largest plants [23,24]. For example, in [25] the number of WWTPs with generation of biogas from anaerobic digestion in USA was estimated to be around 1240 plants out of 15,000, whereas in France [26] only 97 out of almost 20,000 WWTPs applied anaerobic digestion in 2018. Many countries worldwide show a similar profile, with few large plants and a high number of small ones where biogas generation is not likely [4,8,24].

In addition, even though the high number of small plants usually does not represent a very high percentage of the volume of wastewater treated in a country, the negative effects of the economy of scale is frequently observed on their energy consumption figures (as kWh energy consumed/m³ wastewater treated) [10,24]. Hence, their share in energy consumption is often larger than in volume of wastewater [8].

Therefore, the number of small WWTPs with these conditions is huge worldwide and expected to rapidly increase in upcoming years [27]. Simultaneous increasing demand of water and higher protection of the aquatic environment will require new installations too [4]. Many of them will likely be located in rural areas, as in most countries existing wastewater treatment planning has focused on larger urban agglomerations first [4,26]. Possible trends to decentralized sanitation systems would also increase the proportion of smaller plants [28–30]. Thus, other renewable energy options should also be explored to provide simpler alternatives for small plants [31]. Even, as observed in recent studies, they could be applied as complementary systems for the largest ones [32,33].

Renewable energy can be generated from external sources or recovered from the energy embedded in wastewater. As mentioned, for electricity generation chemical recovery through the biogas produced in anaerobic processes is deemed to be the main option but directly depends on those processes and the facilities are complex to operate. Other mature technologies that are frequently being considered at WWTPs, are solar or wind, which are external sources that do not depend on the process, but on the particular characteristics of the site. Their potential and performance directly depend on the site, its surroundings and

its climatic conditions. The main advantages of hydropower are simplicity, flexibility and universal application, without interfering in the treatment process or with the surrounding environment [28–31].

1.1. Management Models and Renewable Energy Strategies in the Wastewater Industry

Several stakeholders must be involved for the effective implementation of new technologies to improve energy performance in the wastewater sector [5,34,35]. Global policies and incentives are usually promoted by national governments with competences for management of water services [5]. Like the pioneer plan in Korea proposed a decade ago, specifically aimed at a reduction of GHGs emissions in WWTPs [36,37] or the recently proposed global plan for improving efficiency in the wastewater sector in Spain [38]. However, although national or even supranational plans might establish basic guidelines, the initiative to actually identify and evaluate the most suitable options and to implement more specific strategies often lies at lower geographical levels [5]. Examples of this can be found in a number of countries, like the study for WWTPs in Madrid region in Spain [39], for Canton de Vaud in Switzerland [40] or for Oregon in USA [41].

There is a wide range of water management models in different countries and even in different regions within a country [5], with regional organisms, basin agencies and municipalities frequently playing important roles as well, the latter often grouped in multi-municipal entities [4,35]. With that, the structure for wastewater governance can be complex and at the same time, the number of WWTPs to manage by the same organism or organization can range from one, to several and sometimes a few hundred plants [4,5]. As a result, the number of stakeholders involved and the level where the decision-making process for the implementation of renewable energy technologies at a particular plant takes place, can vary significantly [42,43]. In addition to the regional examples, at private level, similar initiatives from water corporations managing a group of plants from a certain geographical area, are also arising, such as those in Portugal [44] or Spain [45].

Therefore, to assess potential application of a renewable energy technology in this sector, it can be especially relevant to identify the decision-making level for the facilities included within the study area considered.

1.2. Hydropower Technology for Energy Generation in Wastewater Systems

One of the options to consider might be hydropower, where electricity can be generated from the mechanical energy provided by wastewater. In this way, some of the energy embedded in the wastewater, that otherwise would be wasted, could be harnessed [46]. However, as observed by some researchers [47–49] in the urban water industry there is a general lack of awareness and knowledge about this possibility.

Hydropower is a well-known technology for renewable energy generation for electricity supply and more recently has started to be studied at a small-scale as a possible solution for energy recovery at existing water systems [50–52], including WWTPs [53,54]. There is no consensus about the classification of hydropower systems according to their size or capacity. For example, within European countries, the following ranges are usually considered [55]: (i) Large-hydro, with power over 10 MW; (ii) Small-hydro, from 1 MW up to 10 MW; (iii) Mini-hydro, from 100 kW to 1000 kW; (iv) Micro-hydro, from 5–10 kW to 100 kW; (v) Pico-hydro, up to 5 kW. Meanwhile, the limit between large- and small-hydro can be as great as 30 or 50 MW in countries such as the USA, China or India [56–58].

The mini-hydro range usually establishes the limit between the larger hydro systems feeding electricity grids and stand-alone systems, not connected to the grid, providing power for self-consumption in rural or remote areas [59–61].

Previously published academic research on hydropower application to wastewater systems, either developed and applied methodologies for global potential assessment at a country [62,63], or multi-country level [64], or conducted individual feasibility studies at a plant level, experimental as in [65] or theoretical as in [53]. However, no methodology has been proposed to be applied for potential assessment at an intermediate level. None

of these methodologies take into account that in the wastewater industry there could be other important decision-making stakeholders at an intermediate level between individual plant and country level. Direct application of the proposed methodologies at that level might not provide these stakeholders with suitable and complete information for their decision-making processes. Therefore, to be applied at that level a methodology with a different approach is needed. Neither the actual performance of existing sites has been analyzed so far, to be considered in the design of the methodologies.

Moreover, all these studies are usually focused on technical and economic aspects only and the identified global potential for this sector is usually low [64,66]. Environmental assessment in this application has already been studied [67–69]. However, this aspect has not been integrated into the decision-making process yet. Only recently have some authors started to suggest the introduction of additional driving factors, other than economic feasibility, in studies of hydropower potential, with a broader perspective based on the sustainability concept [6,61,70]. In their recent work Adeyeye et al. [49] presented social viability aspects of hydropower application in urban water systems and Llácer-Iglesias et al. [46] also proposed a complementary approach related to energy self-sufficiency, identifying other driving factors for hydropower implementation at WWTPs.

1.3. Aim of This Study

As seen in Section 1.1, for the effective implementation of specific energy strategies within the wastewater sector, suitable intermediate levels between individual plant and national levels should be considered too [42,71]. Therefore, adjustment of the assessment methodologies mentioned in Section 1.2, at the same level as decision-making stakeholders, could provide them with more complete technical information about their renewable energy options [35]. With that, a forward step to real application of renewable energy technologies, as current global targets to tackle climate change require [2,5].

In this context, the main aim of this research is to determine if hydropower technology could contribute to improve sustainability of wastewater systems, as they are essential services for society. To achieve that aim, the objectives of this study are:

1. To analyze the existing framework and real experience of hydropower technology application for energy recovery from wastewater, considering:
2. Previous methodologies for potential assessment proposed in academic papers (described in Section 2.1);
3. Characteristics and performance of real case studies (methods described in Section 2.2 and results displayed in Sections 3.1 and 3.2).
4. To compare both—methodologies with data of the real case studies (methods described in Section 2.3 and results analyzed in Sections 3.1 and 3.2). From that comparison, to propose the basis of a modified methodology for potential assessment, regarding, options for introducing other decision factors and adaptability to provide useful information at a suitable decision-making level.

As a result, a first important contribution of this article is that it provides a new and more complete framework for the practical application of hydropower to wastewater systems, considering the existing real experience in WWTPs worldwide, limited in previous papers to a few illustrative examples with no analysis of their actual performance. From the analysis of performance carried out during this study, areas to focus further research to offer sustainable solutions for the wastewater industry are highlighted in Section 3.4. The results demonstrated that there is an existing experience which is not being used to explore all the options for renewable energy generation in the wastewater sector and hydropower could play a more important role in achieving a sustainable water management.

As another novelty, in Section 3.3 this work presents a new approach to develop potential assessment methodologies, introducing other decision factors than economic feasibility, which is the only aspect considered in previous methodologies. In conclusion, social and environmental factors should also be introduced in the decision-making process,

considering all important stakeholders involved in wastewater management and bearing in mind the whole sustainability concept, needed to reach the SDGs.

2. Materials and Methods

In the initial phase of this research the most relevant methodologies proposed in previous studies for potential assessment of large geographical areas were analyzed (Section 2.1). In a second phase (Section 2.2), the existing background was completed with a search of technical data of existing real case studies, with the aim of gathering as much as possible information about the experience of application of hydropower to wastewater systems. Finally, the results from both phases were compared as described in Section 2.3.

2.1. Methodologies for Hydropower Potential Assessment at Wastewater Treatment Plants

The approach in the analyzed studies usually consists of 2 steps that include:

- Firstly, a technical assessment of the energy generation potential, considering an initial sample of several hundreds of the existing WWTPs from the study area.
- Secondly, an economic feasibility study to determine the profitable plants from the selected potential sites in the previous step, according to several assumptions. This second stage usually allows for more detailed analysis as the number of sites in the sample has been reduced significantly, considering only those with higher potential.

This approach is sketched in Figure 2 and is described throughout this section.

Possible locations for hydropower schemes at wastewater systems include both, upstream the WWTP (using raw or untreated wastewater at the inlet) or on the exit (treated effluent at the outlet of the plant) [50,65,72]. The potential power output is determined by the following general expression:

$$p = \rho g Q H \eta, \quad (1)$$

where p is the power output in W, ρ is the water density in kg/m^3 , g is the acceleration due to gravity in m/s^2 , Q is the volume flow rate of water passing through the hydraulic machine in m^3/s , H is the available head in m and η is the overall efficiency of the system, including turbine, generator and transformer efficiencies. For an installed hydropower system, its general performance can be summarized and roughly assessed with yearly data to obtain the ratio:

$$\text{Capacity factor (\%)} = \frac{\text{Energy generated}}{\text{Installed power } 8760} \quad (2)$$

where the energy generated is the actual generation of the hydropower system per year in kWh/year, the installed power is the capacity of the installed hydropower system in kW and 8760 are the number of working hours in hours/year, assuming 365 day/year and 24 h/day [59,70].

The selection of suitable machinery is very important [50,73]. According to the working conditions there is a wide range of hydraulic machines. Factors to consider include for instance if the system is pressurized or operates at atmospheric pressure and the type of mechanical energy to be harnessed (potential, kinetic, pressure) [50,52]. Archimedes screws and gravity water wheels are the most frequent examples of hydraulic machinery in open channels [56,58]. Conventional turbines can be classified into reaction (Francis, Kaplan, Deriaz, Propeller) and action or impulse turbines (Pelton, Crossflow, Turgo) [52,57,74]. Later developments of hydropower technologies have also promoted the application of adapted machines such as pumps working as turbines (PATs) or tubular propellers, suitable to the smaller scale ranges [48,52]. The machine selection will ultimately depend on the combination of values for the water flow rate Q and the available head H in a particular case. The hydraulic efficiency for each type of machine within the foreseen working range must be evaluated too, as flow rate fluctuations can significantly affect the actual energy generation [60,75].

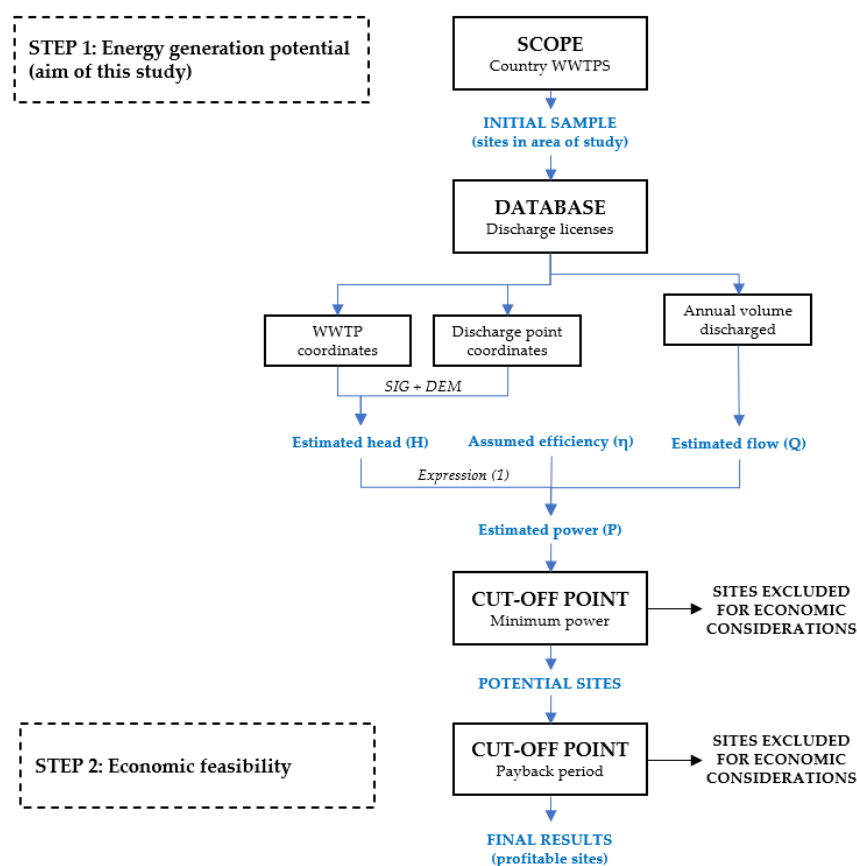


Figure 2. General approach in existing methodologies.

As mentioned, the general process followed in the existing methodologies could be represented as shown in Figure 2. This diagram summarizes the common approach although there are some differences among them. In the following paragraphs the main aspects for each analyzed methodology are described and, finally, summarized in Table 1.

In 2014 Power et al. published the first academic paper describing a methodology specifically designed to assess the potential of hydropower technology applied to the wastewater sector at a country or multi-country level, namely for Ireland and the UK [62]. The initial sample included 100 WWTPs in Ireland, although in a second stage a few additional potential sites in the UK were also added. PATs and different types of reaction turbines were considered, Francis, Propeller and Kaplan. Because of the characteristic flow oscillations at WWTPs, Kaplan turbines were selected to be applied in all cases, as they are suitable for low heads and show high efficiency performances for a wide range of flow rates. To assess the potential power for each site the Equation (1) was used, assuming 65% efficiency. Using data from 5 real case studies, the authors adapted equations proposed in previous articles to compute the installation costs, and hence, the economic viability. Then, based on economic criteria other assumptions were made for the selection of sites: a minimum power of 3 kW, to be considered as potential sites in the first step and, from those, a maximum payback period of 10 years, to be regarded as profitable in the second step. Thus, only 14 potential sites in Ireland and 11 additional sites in the UK were detected. After the application of all the selection criteria, the results indicated that only 8 sites could be considered as profitable (3 WWTPs in Ireland and 5 WWTPs in the UK), corresponding to the largest plants from the area of study.

Other remarkable contributions from that research included a sensitivity analysis conducted to study the influence of variations of flow rate on the results and a method to find the optimal design flow for the hydropower system to maximize power output. Considering the influence of the ratio actual flow rate vs. design flow rate on the Kaplan

turbine efficiency, the authors concluded that over-design might be more suitable. The study also highlighted that allowing for possible changes in policies, including incentives for renewable energy generation and oscillations in energy prices, there might be significant fluctuations and that more precise results would require site specific feasibility studies.

Further work from that research group confirmed and completed the study with other important considerations. In [76], Gallagher et al. similarly applied the methodology to different water systems in Wales and Ireland and some key issues regarding the economic feasibility are highlighted. Hydropower can be integrated into existing water systems without interfering in the main purpose of those facilities, harnessing an excess of energy that otherwise would be wasted. The main costs are related to the turbine and generator costs. Current technology challenges are related to the variations of flow rate, as they directly affect the efficiency and the size. The smaller the size, the less economically viable the implementation results. However, if more efficient and affordable machinery is developed and future energy policies improve incentivization, the criteria to be applied might differ and, therefore, the results might be different too. In [73], the authors studied deeply the effects of the variations of flow rate on efficiency for 4 different machinery options (Francis, Propeller, Kaplan and PATs) and provided some estimations to determine the optimum selection and design flow for each of them. Further lines of research pointed to explore options to overcome flow modulation by optimizing possible combinations of low-cost PATs. Experimental and demonstration sites were also considered extremely important to achieve that goal. In additional studies [67,77,78], the environmental perspective of micro-hydropower was deeply analyzed, applying Life Cycle Analysis (LCA) concepts and methods. The results have not been integrated into the potential assessment methodologies for WWTPs, although they demonstrated the positive environmental impacts of applying this technology to existing water infrastructure and provide valuable information if environmental factors are to be considered.

In 2017, Bousquet et al. [63] carried out a similar study for Switzerland, which could be considered one of the leading countries, with South Korea, in the application of hydropower to WWTPs [46,79,80]. As a framework to develop their work, that study included an inventory of 17 existing cases studies worldwide. In this article, the methodology to obtain the input data for each site to assess the potential is also described. Available gross heads were estimated using Geographic Information Systems (GIS) and a Digital Elevation Model (DEM), from the UTM coordinates of the WWTPs and the corresponding discharge points. To calculate potential power the average flow rate of the plant was used, assuming the net head as 90% of available gross head and overall 70% efficiency. The initial sample included 900 WWTPs in Switzerland and a distinction was made between inlet (untreated wastewater upstream) and outlet (treated effluent downstream) position for the hydropower system. The cut-off point for this first step was established at a potential power of 5–10 kW, corresponding to a minimum generation of 50 MWh/year. In the second part of this study, several economic equations were presented to compute the costs. To calculate profitability more detailed calculations were carried out, taking into account the optimum design flow, characteristics of pipe connection to compute net head and the most suitable machinery, considering Kaplan and Pelton turbines, PATs and Archimedes screws. The results for the outlet position (final effluent) showed 41 potential sites, 14 of which were considered as profitable, whereas at the inlet position (untreated effluent) 65 potential sites were detected, regarding only 5 of them profitable. From the analysis of different machinery, 2 types were considered most suitable, depending on the profile—Pelton turbines for sites with high available H and Archimedes screws for plants with high Q. Finally, comparing the selected sites with the preliminary inventory of 17 case studies, for the outlet position the 6 identified sites in Switzerland were included. However, the results for the inlet position did not include the existing Swiss site in that inventory (Profay). The main conclusions were similar to the study of Power et al. [62] highlighting that in general the results of the methodology should be considered context specific.

More recently in [66] a similar methodology was applied to conduct a study to assess the potential at the outlets of fish farms, industrial and municipal WWTPs in Spain. The input data for potential assessment were extracted from the discharge licenses from the main 7 river basins organisms in the country, using the annual volume discharged to compute the average daily flow. As in the previously described methodology, available heads were estimated from the UTM coordinates for the WWTP and the discharge point, using GIS and DEM. In this case the cut-off point was established in a minimum power of 2 kW, again for economic reasons. The installation of PATs was considered for all cases, assuming an efficiency of 60%. As the available head at WWTPs is usually low and the number of sites in the initial sample was very high (16,788 sites), those that needed a head greater than 15 m to produce that power were discarded in a first screening. For the remaining sample (471 sites) the potential power was estimated and after applying the cut-off value, the results showed 95 municipal WWTPs to be considered.

The last study to be analyzed, broadened its scope to a multi-country level, including drinking, irrigation and wastewater networks [64]. As part of the REDAWN project [81], the study area included Ireland, Northern Ireland, Scotland, Wales, Spain and Portugal. The methodology followed to obtain the input data for WWTPs and to compute the potential power was as described for the previous studies. According to the authors installation of hydropower systems under 2 kW might not be economically viable and, therefore, that value was established again as the limit for selection of potential sites. As current PATs technology makes them reliable between 2 and 50 kW, these were selected to be applied to all cases assuming a conservative 50% of efficiency. From an analyzed sample of 8828 sites, including all 3 types of systems, 878 corresponded to WWTPs. From those, 535 were in Ireland and 343 in Spain, the latter already preselected from the study conducted in [66]. According to the project reports [81], as in all other studies, the samples were significantly reduced throughout the screening process after applying the assumptions and cut-off limits. Thus, 15 plants in Ireland and 89 in Spain were finally, considered. Other results of the study were provided as total energy potential and global values for each sector and country, concluding, however, that the potential for wastewater systems was the lowest, when compared with drinking and irrigation networks.

Table 1 shows a summary with the main features of the described methodologies.

Table 1. Summary of the analyzed methodologies for hydropower potential assessment applied to wastewater systems.

Scope	Urban WWTPs			Cut-Off Points	Main Assumptions and Remarks	Ref.
	Initial	Potential	Results			
Urban WWTPs (Ireland + UK)	>100	14 + 11 (Ireland + UK)	3 + 5 (Ireland + UK)	Power > 3 kW Payback <i>p.</i> <10 years	65% efficiency Kaplan $Q_{\text{design}} = 1.3 - 1.5 Q_{\text{average}}$	[62]
Urban WWTPs (Switzerland)	900	106	19	Power > 5–10 kW (gen. > 50 MWh/y) Payback period	H_{pot} : GIS, DEM data $Q_{\text{pot}} = Q_{\text{average}}$ Upstream + Downstream 70% efficiency Pelton (H) + Screw (Q)	[63]
Fish Farms + Industrial + Urban WWTPs (Spain)	16,788 (3 types)	471 (first screening 3 types)	95 (urban WWTPs)	Power > 2 Kw (from H required) *	H_{pot} : GIS, DEM data $Q_{\text{pot}} = Q_{\text{average}}$ 60% efficiency PAT Most H < 10–12 m *	[66]
Drinking + Irrigation + Urban WWTPs (Ireland + N.Ireland + Wales + Scotland + Spain + Portugal)	535 (Ireland)	66 + 343 (Ireland + Spain)	15 + 89 (Ireland + Spain)	Power > 2 kW	H_{pot} : GIS, DEM data $Q_{\text{pot}} = Q_{\text{average}}$ 50% efficiency PAT	[64,81]

2.2. Real Case Studies of Hydropower Applied to Wastewater Systems

Following the methodology described in [46] and bearing in mind the main purpose of this study, a literature search with a broad approach was conducted. This is particularly relevant when, as in this study, the objective is to examine the state of the art of the current application of a technology to real cases, with the aim of utilizing what is referred to as “wisdom of practice” [61,82]. Hence, using internet search engines as well, to retrieve other types of documents available at websites from different stakeholders, the inventory of real case studies presented by the authors in [46] was completed. This included private companies such as turbine manufacturers, engineering contractors, water managing companies, consultancy services, energy and wastewater practitioners, etc., and also, national and local government authorities, water agencies and wastewater- or energy-related institutions or associations. When a real case study was identified, the search was extended trying to obtain the technical data and actual performance information of the hydropower system installed. Thus, additional sources included specific corporate websites or plant performance reports, practitioner magazines and other press articles.

Appendix A shows all sources of public information analyzed during this research to extract the data for the 49 identified real case studies, which will be displayed in the tables in the following Section. When different sources for a case study were found, all of them were analyzed, the data were compared and the most recent values were preferred to be included in the tables.

2.3. Analysis of Methodologies and Comparison with Real Cases

All the methodologies analyzed (Table 1) have some aspects in common. On the one hand, as mentioned, they are applied to large geographical areas, namely at a country or multi-country level. However, in some countries, for example Spain [34,38], other regional stakeholders like regional governments also have an important role in the decision-making process [5]. On the other hand, the potential assessment is solely based on economic feasibility, establishing some cut-off points to reduce the initial samples to the most profitable sites, according to all the technical and economic assumptions made. With that, the main decision factor is an acceptable payback period [76] and usually this is only achieved in the largest plants with high flow rates. Thus, the results show that most of WWTPs will not likely present an attractive target market for hydropower technologies manufacturers as the desired conditions of high H and high Q are not the most frequent at the majority of facilities and seldom combined. Nevertheless, as already observed in some of those studies and more recently also mentioned in [9,46], in the current energy framework, economic feasibility could vary significantly and, therefore, the results. These depend on a number of parameters that nowadays are continuously changing, including policies, incentives, or market prices for both energy and technologies [9].

Furthermore, some of these articles include a few real case studies as examples but their data are only used to validate the assumptions made regarding economic issues [62,63]. No further analysis of technical data or performance has been carried out to date. This suggests that, even though all these studies provide very valuable information for this area of research, some aspects could be modified to adapt the methodologies to be applied in future studies with a different approach and regarding existing real experience. The new approach presented in this study, however, does consider a preliminary analysis of the technical performance of the existing hydropower systems installed. For the identified real case studies the search was broadened trying to obtain the following data: Scheme location (inlet or outlet), type of hydraulic machine, hydropower flow design Q (and, if also available, the average flow rate of the plant), available head H (gross/net), installed power capacity P and annual electricity generation. From those data, applying Equation (2), the capacity factors were computed to assess actual performance.

All the obtained data and results are displayed in the Tables in Sections 3.1 and 3.2, where they are also discussed in comparison with the assumptions made in the analyzed methodologies (Table 1).

3. Results and Discussion

3.1. Analysis of Real Case Studies Profiles

Seeing the limitations to find publicly available data for the wastewater sector [46,83] and that there could be more existing experience than assumed, the search according to the methodology followed in [46] was broadened further as described in Section 2.2. Thus, the results might offer a new perspective and, bearing in mind the sources of data, their analysis might provide a valuable basis for further research and improvement [61,82]. All sources utilized during this research for the real case studies inventory and their data extraction are included in Appendix A.

According to that, up to 49 existing real case studies of hydropower application to wastewater systems were found, as shown in Table 2. To the best of the authors knowledge, this represents the most comprehensive inventory up to date, with almost 3 times the number of sites included in [63], that only considered 17 existing sites to develop their methodology. These results confirm the lack of awareness about this methodology in the wastewater industry, already highlighted by some authors [46,49,76] and that there might be valuable real experience, which has not been evaluated yet and it could be worthwhile to explore further.

Table 2 shows all the identified real case studies, with their basic data, name of the WWTP (case study), location, year of installation and installed power. An arbitrary ID number has been assigned to each site, to enable traceability throughout this paper. The installed power is usually one of the few published data, so this allowed to classify most of them according to the size ranges mentioned in Section 1.

The different locations show an interest for this technology worldwide, as shown in Figure 3, with existing sites in 14 different countries. There are clearly 2 leading countries in number of sites already applying this technology, Switzerland and South Korea, with 16 and 11 case studies, respectively. Spain and Germany follow this classification with 3 plants each. As concluded in the studies analyzed in Section 2.1, the potential seems to be higher in large cities, which is related to high flow rates. However, as indicated in [46], most of these WWTPs also use biogas and other technologies such as solar or wind for energy generation.

From the 46 cases with published data about installed power, 17 could be classified as micro-, 22 as mini- and 7 as small-hydropower, considering the whole system, that is accounting for all turbines installed. None of them falls into the range of pico-hydropower, being 6.6 kW, the lowest power found (ID 10). This distribution according to the hydropower system size is plotted in Figure 4. This shows there is a wide range of needs and possible combinations, reinforcing the idea that, even when a high number of plants is being analyzed, the methodology should allow to introduce some case-by-case considerations, in relative terms. Compared to the cut-off points established in the methodologies summarized in Table 1 (2–10 kW), usually around the limit between the pico- and micro-hydro ranges (about 5 kW), all of them are well above that limit. One reason for that might be not only a higher potential, but also a higher accessibility to knowledge and resources in larger plants, usually pioneers in the implementation of new technologies, as observed in [35,42,46].

Table 2. Inventory of the 49 real cases studies of hydropower application to wastewater systems found during this research.

ID ¹	Case Study	Location ³	Year ⁴	Installed Hydro Power (kW)	Range
1	Plobb-Seefeld ²	Seefeld Zirl-AT	2005	1192	Small
2	Ebswien	Vienna (Simmering)-AT	2009, 2013	400	Mini
3	Chaux-de-Fonds ²	La Chaux-de-Fonds-SW	2007, 2016	1532	Small
4	Le Châble Profray	Val Bagnes, Verbier (Valais)-SW	1993, 2008	350	Mini
5	La Douve 1	Aigle, Leysin (Vaud)-SW	1989, 2000	430	Mini
6	La Douve 2	Aigle, Leysin (Vaud)-SW	2001	75	Micro
7	L'Asse ²	Nyon (Vaud)-SW	1990	215	Mini
8	Coppet-Terre Sainte (SITSE)	Commugny (Vaud)-SW	2014	110	Mini
9	Grächen	Grächen (Valais)-SW	2011	262	Mini
10	Iseltwald	Iseltwald (Berna)-SW	2014	6.6	Micro
11	Engelberg	Engelberg-SW	2010	55	Micro
12	Morgental (Hofen) ²	Steinach (St. Gallen)-SW	1916, 2014	1260	Small
13	Aïre	Genève-SW	before 2015	200	Mini
14	Meiersboden (Rabiosa) ²	Chur-SW	2016	194	Mini
15	La Saunerie	Colombier (Neuchâtel)-SW	2014	15	Micro
16	Schwyz ²	Seewen-SW	2011	15.5	Micro
17	La Louve ²	Lausanne-SW	2006	170	Mini
18	Kuesnacht-Erlenbach-Zumikon ²	Kuesnacht-SW	2016	N/A	N/A
19	Chartres Métropole ²	Mainvilliers-FR	2020	200	Mini
20	Emmerich (TWE)	Emmerich am Rhein-GE	2000	13	Micro
21	Böhmenkirch ²	Roggental-GE	2001	40	Micro
22	Buchenhofen	Wuppertal-GE	1966, 2012	560	Mini
23	Esholt	Bradford (Yorkshire)-UK	2009	175	Mini
24	La Cartuja	Zaragoza-SP	2015	225	Mini
25	Sur	Getafe (Madrid)-SP	before 2014	180	Mini
26	La Gavia	Madrid-SP	before 2017	75	Micro
27	Glina	Bucharest (Ilfov County)-RO	before 2019	426	Mini
28	Brussels-North	Brussels-BE	before 2019	640	Mini
29	Namur (Lives Brumagne)	Lives-sur-Meuse (Namur)-BE	2016	N/A	N/A
30	North Head	Sydney-AU	2010	4500	Small
31	Gippsland Water Factory ²	Maryvale (Gippsland)-AU	2010	300	Mini
32	As samra	Amman City-JO	2008	1660 + 1614	Small
33	As samra II	Amman City-JO	2015	515	Mini
34	Asan	Chungnam asan-KR	2000	36	Micro
35	Cheonan	Chungnam Cheonan-KR	2002	40	Micro
36	Jinhae	Gyeongnam jinhae-KR	2004	10	Micro
37	Shinshun	Daegu-KR	2005	139	Mini
38	Seoksu	Gyeonggi Anyang-KR	2007	400	Mini
39	Seobu	Daegu-KR	2010	74	Micro
40	Chungju	Chungju-KR	2011	135	Mini
41	Nan Ji	Seoul-KR	2014	N/A	N/A
42	Tan Chun	Seoul-KR	before 2017	60	Micro
43	Joong Rang	Seoul-KR	2015	60	Micro
44	Seo Nam	Seoul-KR	2015	100	Micro
45	N/A	Taichung-TW	before 2008	68	Micro
46	Hsinchu	Hsinchu-TW	before 2008	11	Micro
47	Deer Island	Boston (Massachusetts)-US	2002	2000	Small
48	Point Loma	San Diego-US	2001	1350	Small
49	Clarkson	Mississauga-CA	2015	225	Mini

¹ Identification number. All sources of data for each case study are displayed in Appendix A. ² Particular configurations: Receiving input (inlet flow) or generated output (electricity) exchanged with other sites outside the boundary limits of the wastewater treatment plant.

³ AT: Austria; SW: Switzerland; FR: France; GE: Germany; UK: United Kingdom; SP: Spain; RO: Romania; BE: Belgium; AU: Australia; JO: Jordan; KR: South Korea; TW: Taiwan; US: United States; CA: Canada ⁴ Year. Date first installation, date last update. "Before": Date of installation not available, the year of the first mention found as existing case has been displayed as a reference. N/A: Not Available.

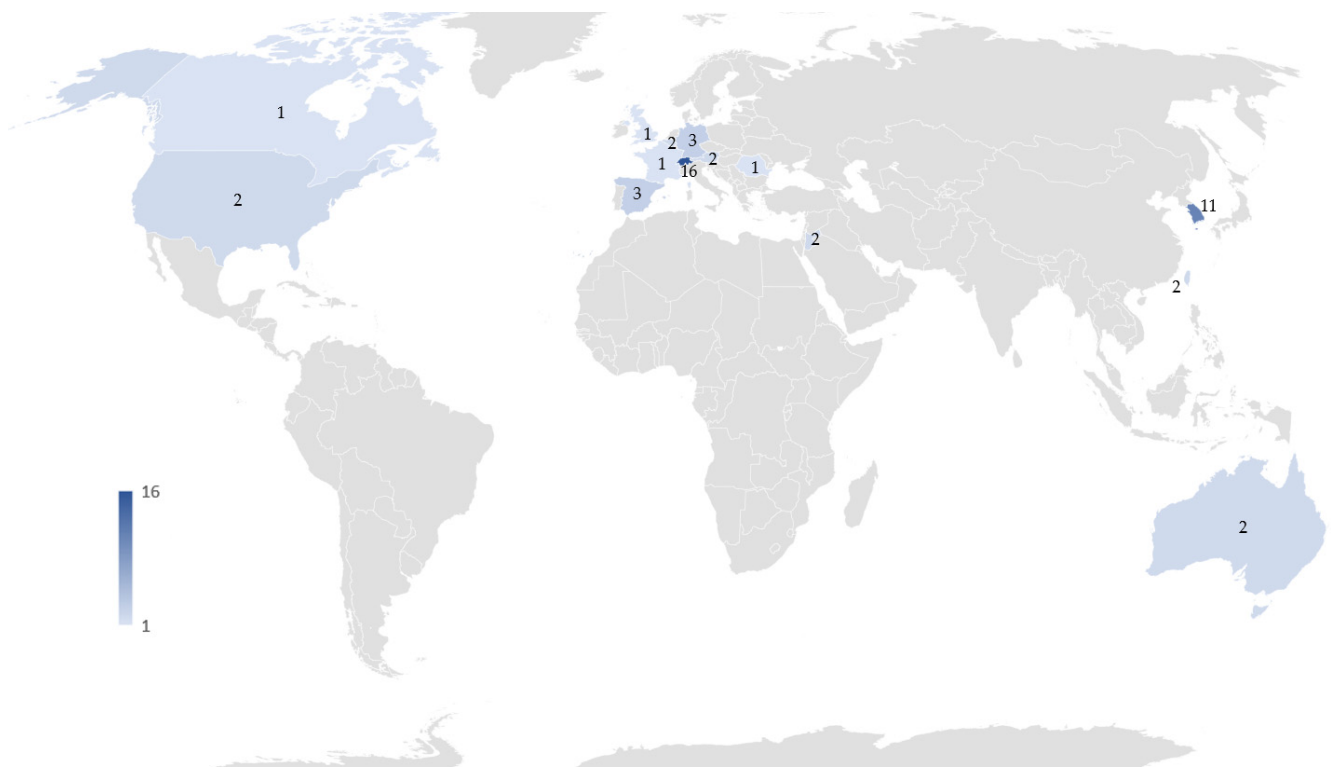


Figure 3. Location of the analyzed case studies (number of sites).

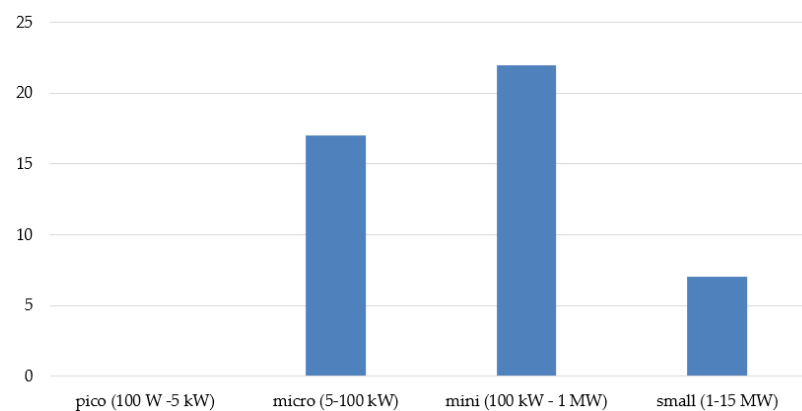


Figure 4. Distribution of hydropower systems size: Number of case studies per size range.

In addition, the conclusions in previous studies that hydropower potential for this sector certainly is not very high [62,63,66], especially when compared with other water systems [64,81], or renewable energy technologies [15,16,24], are confirmed by the absolute figures of installed power. However, the distribution showed in Figure 4 is also consistent with the idea that the installation of hydropower in wastewater systems should mainly be aimed for electricity generation for self-consumption [46]. This use on-site would be generally the case for WWTPs, as being energy producers to feed electricity grids could only be achieved in sites with very exceptional conditions [60,61]. As wastewater treatment processes are very energy intensive, to harness some of the energy embedded in the wastewater, in this case, mechanical energy, would contribute to some extent to reduce electricity consumption from the grid and with that, to increase energy independency and sustainability [46,84]. That means that, in most cases, hydropower cannot be compared to biogas [15], which clearly present a much higher potential, given that anaerobic processes take place in the plant [9,24]. The real potential of hydropower should be to become a “low-hanging fruit” technology, easy to identify and implement [46,77,85].

For that, the full range of technical options of pico-hydro systems might also be explored [60,65,86] to provide solutions adapted to the needs of the numerous small plants worldwide. In particular, recent developments in low head applications would be of special interest to be deemed as possible options [48,57,65]. Reliable hydraulic machinery adapted to different working conditions would benefit not only the wastewater sector, but also drinking and irrigation water systems, particularly in rural or isolated areas and developing countries, where hybrid off-grid solutions could play a crucial role in the near future.

Only for two case studies (ID 45, 46), no more available public data than those displayed in Table 2 were found. For the rest of the sites, Table 3 shows all technical data found about the characteristics of the site and the hydropower system installed.

Concerning the hydropower scheme location, as mentioned, the options to consider are upstream the WWTP (raw or screened wastewater) or downstream (treated effluent at the outlet). Regarding this, only the methodology in [63], applied to Switzerland, considered both options, as in the upstream configuration, additional factors must be taken into account and their design and operation might be much more complex.

As Figure 5 shows the number of existing sites with the hydropower scheme located at the outlet is notably higher and from the individual data in Table 3 can be seen that this is the usual option for large plants. However, as observed in Table 3 as well, the upstream scheme could be an interesting option to be deemed in areas with favorable topography like Switzerland and high available heads along the sewage network. It could also be of interest in those cases with particular configurations (see footer number 2 in Table 3), in networks with different municipalities sharing a WWTP.

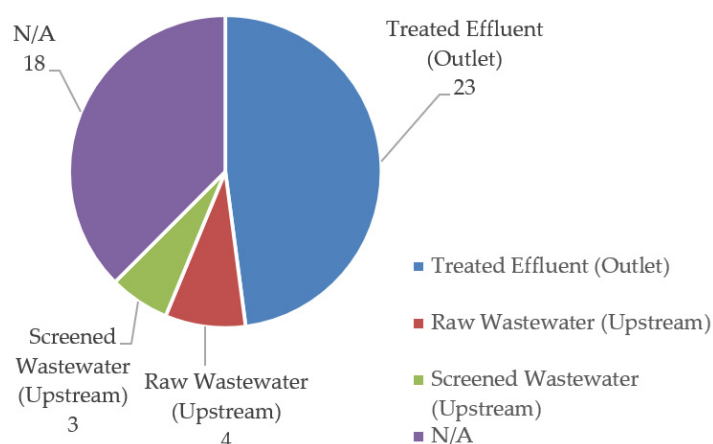


Figure 5. Hydropower scheme location in case studies.

Concerning the Q , if both values were available, the WWTP average effluent flow rate and the design flow of the hydropower, they have been displayed together to allow for comparisons. Even though it seems that in such cases the design flow of the hydropower is usually higher than the plant flow, only in very few cases were reliable data for both found to enable drawing further conclusions. Special mention should be made for the particular configurations (footer 2 Table 3), where no relationship between those values could be established, as the flow passing through the turbine does not correspond to the total inlet or outlet flow of the plant. Similarly, when values for the gross and the net available H were found, both have been displayed. Again, the available data did not allow to draw strong conclusions. The only remarkable conclusion when considering Q and H values, is that the existing case studies clearly show two different profiles: either plants with very high available H , or large plants in big cities with significant Q , but usually low available H .

Table 3. Technical data of hydropower systems installed in real cases studies found during this research.

ID ¹	Case Study	Scheme ³	Q (m ³ /s) WWTP /Design	H (m) Net/Gross	Hydraulic Machine (Number, Type) ⁴
1	Plobb-Seeefeld ²	TE	0.089/0.250	-/625	N/A
2	Ebswien	TE	6.206/6.500	-/5	1 Screw + 1 Kaplan
3	Chaux-de-Fonds ²	TE	-/0.500	380/393	1 Pelton
4	Le Châble Profray	RWW	-/0.100	430/449	1 Pelton (V)
5	La Douve 1	N/A	-/0.108	510/559	1 Pelton
6	La Douve 2	TE	-/0.108	79/83	1 Pelton (V)
7	L'Asse ²	N/A	-/0.290	-/94	1 PAT
8	Coppet-Terre Sainte (SITSE)	TE	0.083/0.170	77/-	1 Pelton
9	Grächen	N/A	-/0.089	351/-	1 Pelton (H)
10	Iseltwald	N/A	-/0.0095	120/-	1 PAT
11	Engelberg	TE	0.069/0.139	-/50	1 Pelton
12	Morgental (Hofen) ²	TE	0.174/0.840	190/-	1 Pelton (H)
13	Aire	TE	2.000/3.200	5/-	1 Kaplan
14	Meiersboden (Rabiosa) ²	SWW	-/0.015	-/522	1 Pelton
15	La Saunerie	N/A	0.127/0.240	4.5/-	1 Turbine
16	Schwyz ²	TE	0.242/0.250	-/7	N/A
17	La Louve ²	RWW	-/0.120	-/180	1 Pelton
18	Kuesnacht-Erlenbach-Zumikon ²	SWW	-/-	-/180	N/A
19	Chartres Métropole ²	TE	0.400/0.800	-/-	N/A
20	Emmerich (TWE)	N/A	0.185/0.400	3.8/-	N/A
21	Böhmenkirch ²	RWW	0.017/-	-/100	1 Pelton
22	Buchenhofen	N/A	1.309/10.000	7/-	1 Kaplan
23	Esholt	SWW	-/2.678	8.2/-	2 A.Screw
24	La Cartuja	TE	1.643/-	8.5/-	1 SemiKaplan
25	Sur	TE	2.895/2 × 3.500	3.2/-	2 Turbines
26	La Gavia	TE	0.965/-	-/-	1 Turbine
27	Glina	TE	7.851/-	-/-	N/A
28	Brussels-North	TE	3.260/-	-/-	N/A
29	Namur (Lives Brumagne)	TE	0.249/-	-/6	1 Turbine
30	North Head	TE	3.889/3.500	-/60	2 Kaplan
31	Gippsland Water Factory ²	N/A	0.405/-	-/-	Kinetic
32	As samra (inlet)	RWW	3.000/2 × 1.250	78/104	2 Pelton (V)
32	As samra (outlet)	TE	-/2 × 2.300	41/42	2 Francis (V)
33	As samra II	TE	4.213/-	-/-	1 Francis
34	Asan	TE	0.521/0.370	6.9/7.2	1 Kaplan
35	Cheonan	N/A	-/-	2.5/-	1 Kaplan
36	Jinhae	N/A	-/-	1.6/-	1 Kaplan
37	Shinshun	N/A	-/-	3.7/-	1 Kaplan
38	Seoksu	TE	3.472/2.338	14.8/-	1 Kaplan
39	Seobu	N/A	6.019/-	2/-	1 Propeller
40	Chungju	N/A	-/-	6.5/-	1 Propeller
41	Nan Ji	N/A	9.954/-	-/-	Low head (<2 m)
42	Tan Chun	N/A	10.417/-	-/-	Low head (<2 m)
43	Joong Rang	N/A	18.403/-	-/-	Low head (<2 m)
44	Seo Nam	N/A	18.866/-	-/-	Low head (<2 m)
47	Deer Island	TE	15.741/-	2.7/-	2 Kaplan
48	Point Loma	TE	6.103/-	-/27.4	N/A
49	Clarkson	N/A	2.638/-	-/5	N/A

¹ Identification number. All sources of data for each case study are displayed in Appendix A. ² Particular configurations: Receiving input (inlet flow) or generated output (electricity) exchanged with other sites outside the boundary limits of the wastewater treatment plant.

³ Scheme location. RWW: Raw Wastewater (WWTP inlet or upstream); SWW: Screened Wastewater (WWTP inlet or upstream); TE: Treated Effluent (WWTP outlet); N/A: Not Available. ⁴ Machine type. (V): Vertical; (H): Horizontal; N/A: No data Available (neither type nor number of turbines).

A range of types of hydraulic machines have been applied, with predominance of Pelton for heads higher than 50–100 m and Kaplan for lower heads, in coherence with conclusions in [62,63], respectively, summarized in Table 1. Considering the different machinery types, their share is plotted in Figure 6.

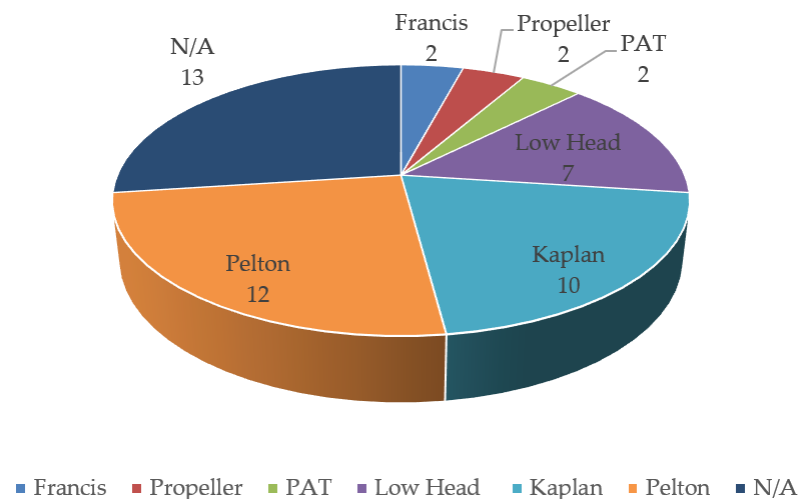


Figure 6. Hydraulic machinery types applied in case studies.

Application of PATs was only found in two sites (ID 7, 10), although most of the cases in Table 2 show power figures above the upper limit of 50 kW recommended in [64] for the consideration of these machines. Low-head solutions have been grouped, including screws (ID 2, 23) and hydrokinetic turbine (ID 31), although application of these solutions has been only observed in seven sites, four of them (ID 41–44) of unspecified type.

All this illustrates again that the pico-hydro range and the low head options have not been fully explored in this application yet. The lowest cut-off point in the analyzed methodologies was established at 2 kW. Nevertheless, according to some studies in small scale hydropower, machines of only a few hundred watts have been recently developed by different manufacturers worldwide [58,65,74]. Therefore, regarding the values indicated in those studies, although economic feasibility obviously decreases with size, from a technical point of view, solutions from 100 W could be considered for energy recovery. According to all this, it might be of interest to deepen current knowledge about the possibilities of application of low head and small-scale hydropower options for the recovery of energy in the wastewater sector, particularly at the myriad smaller plants. Experimental pilot plants and full-scale prototypes would be particularly useful to adjust the performance of hydraulic machinery to the needs of small WWTPs and, therefore, the potential market.

3.2. Analysis of Real Case Studies Performance

In those cases where available data of annual electricity generation from the installed systems were found, comparisons were made with the installed power to compute the capacity factor according to expression (2). This value summarizes the actual overall efficiency of the hydropower system in a year, assuming continuous working for 365 day/year and 24 h/day and regarding the maximum theoretical power generation. These results are shown in Table 4. Comparing the foreseen overall efficiency in the analyzed methodologies with the average values of capacity factors obtained, the analysis shows that the latter are below the assumptions and, therefore, actual power output might be lower than expected, from the design conditions.

Table 4. Electricity generation and capacity factor of hydropower systems installed in real cases studies.

ID ¹	Case Study	Energy Generation (GWh per Year)	Capacity Factor (%)
1	Plobb-Seefeld	5.5	52.7
2	Ebswien	1.8	51.4
4	Le Châble Profray	0.843	27.5
5	La Douve 1	1.85	49.1
6	La Douve 2	0.33	50.2
7	L'Asse	0.5	26.5
8	Coppet-Terre Sainte (SITSE)	0.338	35.1
9	Grächen	0.858	37.4
11	Engelberg	0.202	41.9
12	Morgental (Hofen)	3.672	33.3
14	Meiersboden (Rabiosa)	0.339	19.9
16	Schwyz	0.06	44.2
17	La Louve	0.46	30.9
21	Böhmenkirch	0.076	21.7
22	Buchenhofen	2.5	51.0
25	Sur	0.51	32.3
26	La Gavia	0.102	15.5
28	Brussels-North	2.1	37.5
41–44	4 WWTPs in Seoul ²	1.905	47.3
47	Deer Island	3.455	19.7
49	Clarkson	0.426	21.6

¹ Identification number. All sources of data for each case study are displayed in Appendix A. ² For the WWTPs in Seoul (Nan Ji, Tan Chun, Joong Rang and Seo Nam) the available data are global, considering all 4 plants altogether.

However, these results are probably due to the negative effect of flow rate fluctuations on efficiency, as important daily, seasonal and yearly fluctuations are usual in WWTPs. To illustrate this, for one of the case studies (ID 47) yearly data for six different years are shown in Table 5. As can be observed, for this given system, the capacity factor ranged from 19.7 to 33.8%. If similar data were confirmed for other cases, that would imply that efforts should focus on improving efficiency of the hydropower systems installed in these facilities, regarding foreseen flow rate oscillations. Therefore, research projects in this area should consider gathering more robust data of current performance of existing real case studies, involving different stakeholders, including WWTPs managing organizations, turbine manufacturers and practitioners. Endorsement of these data could provide a useful basis for further research and future applications, learning from the experience of existing hydropower systems.

Table 5. Annual fluctuations in electricity generation and capacity factor for one case study.

ID ¹	Case Study	Year	Electricity Generation from Hydropower (GWh/year)	Capacity Factor (%)
47	Deer Island	2013	5.916	33.8
		2014	5.920	33.8
		2015	5.861	33.5
		2016	4.243	24.2
		2017	4.449	25.4
		2018	3.455	19.7

¹ Identification number. All sources of data for the case study are displayed in Appendix A.

3.3. Proposed Approach to Adapt Hydropower Assessment Methodologies to the Sustainability Framework

As mentioned, to tackle the energy issue at wastewater systems with a sustainable approach aiming for the SDGs, action is needed from several perspectives, efficiency improvement and renewable energy generation. In the previous sections, the assumptions included in the existing methodologies for hydropower assessment were compared with the background of existing real case studies. Based on the results, in this section, a novel approach is proposed to adapt those methodologies to the sustainability framework.

The basis of the methodology proposed here is focused on the determination of the potential assessment of a sample of WWTPs from an area (Step 1 in the analyzed methodologies). The results of that assessment should provide the basis to conduct the following phase, global feasibility, including the economic analysis (Step 2 in previous methodologies), which is not the aim of this study. Figure 7 shows this novel approach. To enable comparisons with the general approach applied in previous methodologies (Figure 2), the modifications and new considerations proposed in this study are represented in green for Step 1 and orange for Step 2.

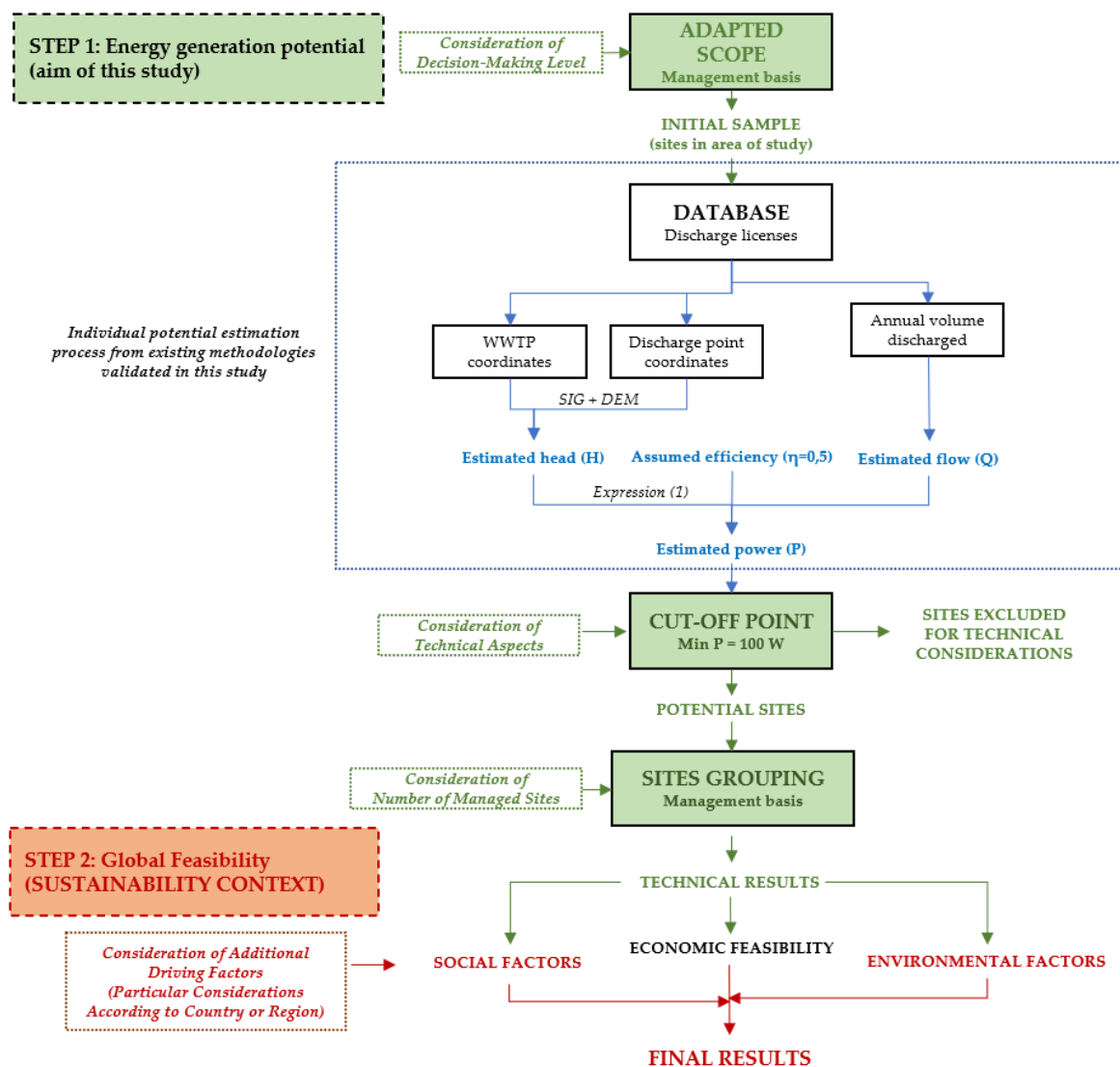


Figure 7. Proposed approach to adapt hydropower assessment methodologies within the sustainability framework.

3.3.1. Scope (Adaptation)

Stakeholders at different levels have different roles in implementing strategies, from planning and policy making to individual plant operation. In many countries, several stakeholders at various intermediate levels also take part of the decision-making process. Hence, the selection of the study area and treatment of data is crucial. Previous methodologies proved to be valuable for estimations at a country level. However, in order to provide information for an approach with a practical perspective, some modifications could be introduced in future studies at a smaller scale level. Adjusting or grouping the sample of plants to be studied to the most likely decision-making level could be useful to achieve that. This means that plants sharing management and goals should be grouped and therefore analyzed not only individually, but also as a whole.

3.3.2. Individual Potential Estimation (Validation)

As mentioned, the hydropower scheme can be located upstream or downstream. According to the data analyzed and regarding the main aim of this study, the scheme at the outlet of the WWTP seems to be the most suitable for a methodology to assess a group of plants in most countries. To properly assess the potential and options of the upstream scheme and possible particular configurations, many additional factors should be considered and in most situations a case-by-case analysis will be needed. Therefore, the proposed approach is focused on the outlet position only.

Concerning the obtention of the individual data for potential assessment, the methods and assumptions made in the analyzed studies, proved to be useful as an estimation at this first stage. The use of DEM and GIS enables us to obtain an approximate value for the available H from the coordinates, provided their accuracy. To obtain Q, the average flow rate of the effluent at the outlet can be estimated from annual volume discharged displayed in basin organisms' reports, assuming 24 h/day, 365 days/year. These simplifications can be especially useful for studies analyzing broad geographical areas with a high number of plants and in developed countries these data are usually available. In other situations, interested stakeholders should provide those data.

To test this, a sample of the case studies was analyzed. From the webpage of the European Environment Agency [87] data of annual volume and coordinates from the EU plants were obtained. The average flow rate was calculated as mentioned and using Google Earth, the elevation between discharge point and WWTP outlet estimated. From these data, potential power was computed assuming a 0.5 global efficiency proposed in the most recent methodologies. Some hydraulic machinery could present higher efficiencies, but this conservative value allows for the consideration of the lower efficiencies in smaller machines and other reduction factors, such as data inaccuracies, flow fluctuations or net available head considering distance and head losses. In a few cases, available data enabled the comparisons between the published data (Tables 2–4) and the potential electricity generation estimated with this methodology. These comparisons are shown in Table 6.

Table 6. Comparison of data from literature review for the hydropower installed and the computed values.

ID ¹	Case Study	Computed H (m)	Computed Q (m ³ /s)	Potential Energy Generation (GWh/Year)	Real Energy Generation (GWh/Year)
1	Plobb -Seefeld	528	0.089	2.019	5.5
2	Ebswien	4	6.206	1.067	1.8
22	Buchenhofen	8	1.309	0.450	2.5
25	Madrid Sur	4	2.895	0.498	0.51
26	La Gavia	12	0.965	0.498	0.102
28	Brussels-North	6	3.260	0.840	2.1

¹ Identification number. All sources of data for the case study are displayed in Appendix A.

In some cases, the method could provide inaccurate results of the real options, but seeing the displayed results, they could be higher or lower. For example, the high deviation in ID 1, might be related to the fact that the real head H (see Table 3) is higher than detected applying the methodology. In the case of ID 22, as also shown in Table 3, there is a significant difference between flow rates Q of the WWTP and the hydropower design. In the case of ID 26, the difference could be due to a low efficiency of the installed system, as the capacity factor for this plant is the lowest shown in Table 4.

Obviously in a following step more accurate data would be necessary, when design conditions for the identified potential sites of the sample have to be determined and from that, the economic study. However, these estimations proved to be adequate enough for the first stage, estimation of the potential assessment of a number of plants, aim of this study. It also reinforces the idea that establishing a strict absolute value of power as a cut-off point might leave out interesting sites.

3.3.3. Other Considerations (Introduction)

Bearing in mind the needs of small plants, when assessing potential of a group of WWTPs managed by a same organization, it could be of interest to reduce the cut-off point to obtain a more detailed picture of the technical feasibility, before undertaking the economic study. The cut-off points in the analyzed methodologies were merely established considering economic feasibility in the current market conditions, with a given value of power, in absolute terms for an individual system. However, as indicated in [46,76], if more affordable hydraulic machinery was available and suitable incentives were developed, this market situation might change. This consideration could be of special interest for the wastewater sector, as the small size of a plant usually entails that electricity generation from biogas is an even more unlikely option. Other technologies should be developed, to provide simple and affordable solutions for at least improving energy performance at small plants.

During this research, it was observed that recent developments in small scale hydropower indicate that a suitable value to consider technical feasibility might be 100 W. Therefore, the proposed cut-off value to consider potential at a single plant could be established with that limit. In this way, the following necessary step to determine economic feasibility would take into account not one isolated small hydropower system, but a group of several ones. As in any other situation where economy of scale makes a big difference, not only the size, but also the number of systems should be considered, both for installation and for operation and maintenance.

Moreover, within the current energy framework, economic feasibility is crucial, but, at the same time, a rapidly changing scenario, with different variables in different countries influencing the results [8,76]. Therefore, other strategic factors tailored to the surrounding conditions should be regarded too [46,49]. No specific guidelines for that can be included in this proposal, as decision criteria and suitable ponderation weights should be adapted to the needs and characteristics of the sample of the studied area and, therefore, beyond the scope of this study.

Nevertheless, some examples can be suggested. One factor could be the consideration of relative values instead of regarding absolute results. For that, the application and evaluation of suitable Key Performance Indicators (KPIs) related to SDG targets could be especially useful. For instance, in rural areas or in developing countries, contribution to energy independence from the grid (% of contribution to self-sufficiency) might be an important factor to consider [84,88]. Other important factors could be pondered, such as real possibilities to apply other renewable energy technologies. For example, hydropower might be an option to consider in areas with very low potential for solar or wind energy generation due to the climatic conditions. Or in regions with a confirmed high number of WWTPs without anaerobic processes and, therefore, no possibilities for biogas generation, even as a complement for all those technologies as shown in [46] or, simply, for those plants

with limited resources to tackle and implement more complex options, as lack of financing is often the main barrier for the application of any technology [4,46].

3.4. Challenges, Limitations and Further Research

From the analysis carried out in the previous sections, it is obvious that several renewable energy technologies should be developed, to provide simple and affordable solutions for at least improving energy performance at small plants. Hydropower might be one of those technologies. Concerning the existing background, the main challenges and limitations that this application faces nowadays are:

- Previous studies of potential assessment of hydropower to recover some energy embedded in wastewater have shown that certainly that potential might not be as high as in other technologies like CHP from biogas. However, they have shown that some potential exists and some energy, that otherwise would be wasted could be recovered.
- There is a low offer of affordable solutions from manufacturers within the smallest ranges and low head options, whilst there could be a large potential market for those.
- Due to the lack of awareness, there is a low demand of this technology from the potential market, in this case, most policy- and decision-makers in the wastewater industry.
- From the technical point of view, flow fluctuations can have a negative effect on efficiency and performance if they are not deemed in the design.

With a clear identification of those challenges, this research sought to provide a new framework for further research in this application establishing suitable connections to fill the gaps found. Thus, further research should consider the following:

- Research projects in this area should consider gathering more robust data of current performance of existing real case studies, involving different stakeholders.
- Further research should also focus on optimizing efficiency performance. However, few small organizations are willing to take risks implementing new technologies and to be pioneers within their sector unless they take part of research funded projects. Therefore, projects with experimental sites to test different machinery options, configurations and working conditions are also needed. Experimental pilot plants and full-scale prototypes would be particularly useful to adjust the performance of hydraulic machinery to the needs of small WWTPs and, therefore, the potential market.
- Of special interest would be the development of affordable market solutions within the micro- and pico-hydropower ranges. Reliable hydraulic machinery adapted to different working conditions would benefit not only the wastewater sector, but also drinking and irrigation water systems.
- Moreover, availability of demonstration sites, real or experimental, would also be essential for disclosure within the wastewater management stakeholders, thus overcoming the current lack of awareness.

To conclude, it is expected that this study can shed light on which areas to explore with further research, for a real and effective application of hydropower technology as a “low-hanging fruit” solution to improve sustainability at wastewater systems.

4. Conclusions

In this research, the existing background of hydropower application to wastewater systems was examined, analyzing published methodologies for potential assessment and publicly available data of real case studies. The analysis of methodologies concluded that economic feasibility is usually the only decision factor considered, although they proved to be useful for estimations at a country level. However, some modifications could be introduced in future studies to offer a closer approach to decision-making stakeholders, at a smaller scale and regarding other driving factors too. The samples of the area of study should be adjusted to the most likely decision-level. To provide a complete picture of

the possibilities at that level, the cut-off value to determine potential before undertaking the economic study, should be based on technical feasibility. Nowadays, this could be established in an individual minimum power output of 100 W. Environmental or social factors such as contribution to energy self-sufficiency and real options to implement other technologies should be considered to ponder the results.

During this research, 49 real case studies were identified, many of them not included in previous articles, providing then a new and more complete framework. Their technical data were analyzed, showing different profiles, proving that no standard solution exists. The analysis of their performance also indicated that improving machinery efficiency still poses a major challenge, particularly regarding the fluctuations of flow rate. Despite the limitations to obtain data, the lack of studies analyzing existing sites so far demonstrated the need to complete this gap of knowledge to develop a better understanding of the current framework before continuing with further research.

In conclusion, even though hydropower does not present the high potential of other renewable energy options such as biogas, with this novel approach, this technology could contribute to reach SDGs, increasing the offer of sustainable solutions to the wastewater sector. If affordable and suitable machinery is developed, hydropower might be considered as a simple solution to be easily implemented in a considerable number of plants worldwide. Of particular interest would be to explore the pico- and micro- hydropower areas, with special focus on low head and improving efficiency, to adjust the current market to the needs of small WWTPs and overcome the current lack of awareness. This might contribute to achieving emissions reduction targets, without facing the risks of undertaking significant modifications of the wastewater treatment processes, facilities or affecting the surrounding environment. If real experience in a technology performance exists, it should be considered as very valuable information to establish a solid framework for improvement. If there is some available energy in wastewater that can be harnessed, that should be considered very valuable too.

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Appendix A

This Appendix shows all sources analyzed during this research to extract the technical and actual performance data for the 49 identified real case studies, which have been displayed in the tables in Section 3.

ID Case Study	Sources of Data
1	References: [15,50,62,72,87]
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