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Energy Self-Sufficiency Aiming for Sustainable Wastewater Systems: Are All Options Being Explored?

Rosa M. Llácer-Iglesias *, P. Amparo López-Jiménez and Modesto Pérez-Sánchez

Hydraulic and Environmental Engineering Department, Universitat Politècnica de València, 46022 Valencia, Spain; palopez@upv.es (P.A.L.-J.); mopesan1@upv.es (M.P.-S.)
* Correspondence: rollaig@hma.upv.es

Abstract: In upcoming years, water demand is expected to boost worldwide, and with that, wastewater generation and the required energy for treatment. Provided that efficiency measures should be implemented at first instance, developments of renewable energy technologies are needed to improve sustainability at wastewater treatment plants (WWTPs). Based on theoretical analyses of literature data, this article presents a novel perspective of the role that hydropower could play in that energy framework. This research applied a new approach compared to previous studies, considering the introduction of sustainability aspects in the decision-making process, other than economic feasibility. With that aim, a broad search of real case studies was conducted, and suitable Key Performance Indicators based on the energy self-sufficiency concept were selected and applied to the identified cases. The findings suggest that there is not a rule of thumb to determine feasibility for hydropower installation and this technology might deserve more attention. This new perspective can help to raise awareness among policy makers, decision managers, or plant operators, of the possibilities hydropower could offer to the wastewater industry in the pathway towards more sustainable systems.

Keywords: energy recovery; wastewater treatment plants; hydropower; renewable energies; sewage systems planning; sustainable wastewater management; wastewater decision-making

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1. Introduction

The plan of action for sustainable development, known as the Agenda 2030, was adopted by the United Nations in 2015 to establish a new global framework towards sustainability. This plan includes 17 Sustainable Development Goals (SDGs) and 169 specific targets, integrating the economic, environmental, and social perspectives. However, these SDGs are not isolated goals, as they can present some important interrelations among them [1–3]. This is the case, for example, of SDG 6 'Clean water and sanitation', SDG 7 'Affordable and clean energy', SDG 11 'Sustainable cities and communities', and SDG 13 'Climate actions'. All these SDGs are interlinked in some points, which share a clear objective: more sustainable wastewater systems [4,5].

The wastewater treatment sector is a large consumer of energy, mainly as electricity. The specific energy demand at a wastewater treatment plant (WWTP) depends on several factors. These include the size of the plant, pollution load, or required quality of the effluent, factors that at the same time, usually determine the choice of the treatment processes to be applied [6,7].

The size of the plant is the main parameter pointed out in most studies, concerning both, volume and pollution load of wastewater treated. Usually, the larger the capacity of the plant, the higher the energy efficiency [8–12]. However, some other factors can have additional effects on this. Seasonality, for example, can dramatically change the characteristics of the received inflow. Therefore, where there are important oscillations in the population served, or when the climatic conditions present very different rain patterns throughout the year (dilution factor), efficiency figures can show a wide range of values [9,12]. Other changes in composition, such as the contribution of industrial effluents or the ratio of organic matter and nutrients, will affect the process and the efficiency too [9,11,13]. Related to this is also the load factor, which represents the ratio between the actual influent received at a plant and its design capacity. It has been found that the most efficient plants have load factors close to 100%, and the least efficient ones are usually oversized [9,12,14].

Concerning the process, several articles indicate that one of the higher contributions to energy consumption is pumping, which mainly depends on the site topography and the planning strategies [9,10,13,15]. However, this contribution is not always considered [10]. Another major factor affecting energy efficiency is the type of treatment, which determines the operations to be carried out at the plant, related to the effluent requirements at the same time [8,11,14]. The stricter the requirements, the higher the number of stages involved (preliminary, primary, secondary, and tertiary wastewater treatment and sludge treatment), and therefore, the energy demand [8–10,12,14,15]. For instance, in a classic activated sludge plant, where the secondary treatment implies aeration, this operation usually accounts for more than half of the energy needs of the plant [9,11,13]. Considering aerobic secondary treatments, which include the widely used activated sludge or extended aeration systems, the technology used for aeration also affects the efficiency. Diffusers show higher efficiency in pollutant removal than turbines, but also higher electricity consumption per volume of wastewater treated [9,11,14].

Therefore, there are some differences in the energy consumption according to the type of treatment, but in almost all cases, the final result is a high energy demand [7,10,15–18]. When comparing this demand with the total energy consumption of a country, it usually accounts for a significant percentage. Data of about 0.8–1% have been estimated for several countries in Europe like Italy, Switzerland, or Germany [12,19–22], 0.5% in Korea [23], 0.25% in China [24], or 0.6% in USA [16,24].

This large consumption of energy is one of the main costs during the operation of a WWTP. Furthermore, it represents an important contribution to the usually high levels of the carbon footprint reported for these facilities [25].

On the one hand, new policies worldwide strive for decarbonization of energy production systems in general [17,23]. Derived from SDG 7, one of the UN specific targets aims for a substantial increase of the share of renewable energy in the energy mix. There is also an increasing number of examples of energy policies specifically aimed at the water and wastewater sector. For instance, at a national level, in 2007, Korea established a general roadmap in the country for an important reduction of GHGs emissions by 2030. A few years later, in 2011, it also developed specific goals for WWTPs, as in 2007, this sector represented a 3.5% contribution to those emissions [26]. At lower geographical levels, many other initiatives promoting the progressive installation of renewable energies at water systems can be found [27].

On the other hand, in the next years, energy needs for wastewater treatment are expected to boost. According to the UN World Water Development Report from 2017 [4], with current trends in population, a 50% of global demand for water in the world could increase by 2030. Moreover, the same report also indicates that about 80% of the wastewater generated around the world is still discharged into the environment without any treatment. Fortunately, as some studies have reported, this has started to change. For example, during the last decade, China showed an increment of 26% new WWTPs installed per year [28], with a significant increase of the volume of wastewater treated, from 17.0 billion m^3 in 2007 to 46.7 billion m^3 in 2015 [29]. Therefore, in upcoming years, the installation of new facilities will be needed, whereas some retrofitting of existing plants will be necessary too [30]. These updates will include a progressive implementation of additional processes, for more advanced treatments than the classic elimination of solids and organic matter, as the requirements for the quality of effluents to be discharged are also increasing. For example, when eutrophication was identified to pose a likely problem for receiving water bodies, removal of nutrients had to be added to the basic process [10,31]. Similarly, awareness of contaminants of emerging concern [21,32] most likely will result in even stricter standards in the future, requiring further treatment as well.

In all this context, within the next years, the already high energy demand for wastewater treatment is expected to grow significantly worldwide [28,33]. With that, both, associated economic costs and environmental impacts will rise too.

1.1. Energy Options for Sustainable WWTPs

As mentioned, current trends and perspectives globally demand to tackle the energy consumption issue for wastewater systems. More sustainable energy performance of WWTPs implies two parallel steps [25].

- First, a reduction of energy consumption. The simplest way by improving operational efficiencies of equipment and facilities. For example, optimizing economies of scale (pumps as large as feasible), increasing the levels of automation of key processes (aeration), or providing specialized training to operators [11,25,34]. Additionally, by implementing processes with lower energy demand, like those based on anaerobic processes for secondary treatment [7,35].
- Second, by the implementation of renewable energy generation technologies [17,21,36], aiming for energy neutrality or self-sufficiency. Within the described framework, this would represent that 100% of the energy consumed at the plant is energy generated by its own from renewable sources [16,26,31,37–39].

Nowadays, total energy self-sufficiency at WWTPs is feasible but still a challenge in most cases. As a rule, there is not a standalone technology that can help a WWTP to achieve total independence from the grid [17,26]. Further, the expected increase of demand for energy in the near future will make that goal even more difficult to achieve [33,36]. Thus, further research is needed in both parallel lines, improving the energy efficiency of the process and facilities, and renewable energy generation on site [25].

Because of this need for renewable energy technologies, during the last decade, a large number of academic and research studies investigating different options and their application to WWTPs have been published. In this case, renewable energies, includes both, external sources such as solar or wind, and internal, when technologies are applied to recover embedded energy from the water. Energy from wastewater can be recovered as chemical, thermal, and/or mechanical energy [10,17,21,40,41].

- Most studies are focused on chemical recovery, as wastewater presents huge potential. The most known technology is the generation of heat and power from biogas, but in more recent years, new options have arisen, such as sludge incineration, microbial fuel cells, microalgae systems, and others, all of them in ongoing research and further development [17,31,36,38,42].
- Thermal energy recovery directly from wastewater, applying, for example, heat pumps, is also being considered as an option, and some scholars are focusing their research on that aspect [43–45].
- Mechanical recovery of energy, like hydropower, however, has received less attention [17,21]. Hydropower technology harnesses energy from the water flow. Power generation is computed with the product of two parameters: Available head (or pressure) and flow rate. In this way, the technical and economic feasibility of any hydropower system is calculated. Based on that, several authors recently studied the potential of small hydropower for improving the sustainability of urban water systems in general [46–51] and wastewater systems in particular [20,52–55].

Regarding real applications up to date, only the most mature technologies are usually applied. The combined generation of heat and power from the biogas obtained in anaerobic digestion is generally regarded as the main contributor to achieve energy self-sufficiency at WWTPs [21,25,38]. For example, in the UK, it was estimated that biogas represents about 90% of the energy generated from renewable sources in the water sector [52]. However, usually only larger plants include anaerobic processes for wastewater treatment, or more commonly, for sludge digestion. According to [36], less than 20% of plants would present this potential.

After biogas, other technologies that are currently being considered at WWTPs for electricity generation are solar or wind. These are external sources and do not depend on the process or size of the plant but the particular characteristics of the site and its climatic conditions. Solar and wind technologies are nowadays widely applied and universally known [16–18,40].

Although hydropower is also a mature technology, as it has been mentioned, the possibility of application to water systems is less known.

1.2. Research Scope

The main motivations for this research stem from the comparison between case studies of hydropower potential and the current framework regarding applications of renewable energy technologies in wastewater systems.

Most of the previously cited studies of hydropower applied to wastewater are usually theoretical assessments, primarily focused on economic feasibility as the main decision-making factor. As small hydraulic machinery is not widely known and applied yet, the current low demand still implies relatively high installation costs. As a result, the potential for hydropower assessed from these theoretical studies is usually limited. Additionally, the rapidly changing circumstances of the current energy market might affect the validity of these results throughout time.

Thirty-six real case studies were analyzed, including several technologies for resources and energy recovery at WWTPs. This comparison showed a few hydropower cases were merely mentioned as examples of the technology [17,21].

Besides, to improve the sustainability of WWTPs, several projects have arisen in recent years, developing some specific tools and guidance documents as help for decision-making within this sector. These projects offer very valuable information, including energy audits and benchmarking data, energy efficiency improvement measures or resources, and energy recovery possibilities. Some of them, such as the European initiatives ENERWATER [17,37,56], POWERSTEP [17,57], or ECAM [58], are specifically focused on energy and associated GHG emissions. Whereas others, like SMART-Plant [17,59] or R3Water [17], have a broader approach and they consider other environmental aspects and their associated impacts, as well as other resources recovery options. Notwithstanding, regarding energy recovery, most of these initiatives have something in common. Electricity generation using biogas is deemed to be the main, or sometimes the only option, while in contrast, hydropower is simply not included as a possibility. Few projects that include hydropower as an option have been found. Moreover, even when it is included, usually very little information endorses this alternative. As a result, hydropower often appears as the least attractive option. Some similar initiatives from the World Bank have also been developed for other regions, such as Latin America and the Caribbean [60] or East Asia and Pacific [61]. These reports do mention hydropower as a possibility, but again, they are focused on biogas as the main alternative for energy generation.

Nevertheless, a wide range of solutions is needed to meet the demand of all types of plants, regardless of their size or treatment process. Aiming for energy self-sufficiency, suitable combinations of several renewable technologies should be explored [17]. Some authors already highlighted the importance of providing all stakeholders in the wastewater industry with complete decision-making tools, broadening their scope and increasing their awareness to achieve more sustainable systems [28]. Whereas all the aforementioned projects strive for that aim, the role that hydropower could play is usually unknown. This lack of awareness about hydropower within the sector has even been reported in recent peer-reviewed studies [62,63]. When not known, often it is just neglected, considering the potential recovery of energy is too low, and not worthwhile to be regarded.

Bearing in mind the strong sustainability concept, where economic, environmental, and social factors should be included and balanced [64], it seems the current framework needs to be improved or completed with a new perspective. The existing theoretical studies in hydropower might be completed with a broader and more applied approach, whereas the holistic energy studies for WWTPs might be provided with more detailed information about the practical possibilities of hydropower. This research aims to start to build that bridge.

Thus, the main purpose of this study was to investigate if hydropower could help to improve sustainability in wastewater systems. To achieve that goal, the following sub-goals were defined:

- To conduct an intensive search trying to identify all possible real case studies of hydropower application to wastewater systems existing up to date.
- To extend the search trying to find information related to the energy profile for each identified case, concerning renewable technologies applied.
- To select the most suitable energy Key Performance Indicators (KPIs) to frame the current situation and apply them to the obtained literature data.

As a result, this paper presents a novel perspective of possible driving factors for the implementation of hydropower in wastewater systems. As a novelty, sustainability KPIs based on the energy self-sufficiency concept were applied instead of economic considerations.

According to this, the final aim of this paper is to illustrate the practical possibilities, usually unknown for most stakeholders, that hydropower could offer to the wastewater sector in the pathway towards more sustainable systems.

2. Key Performance Indicators Applied to WWTPs

The methodology followed in this study could be subdivided into two main phases: case studies and energy data search, and energy KPIs selection and application.

2.1. Data Search applied to WWTPs

As a first stage, an intensive search was conducted, following the steps detailed below. This process was designed regarding the experience provided by Adams et al. [65] in the application of well-known concepts of systematic review within the sustainability framework.

1. Scope definition: Inclusion and exclusion criteria;

The first step was to define the scope and the search strategy, bearing in mind that the main aim of the research was to gather information from real case studies worldwide and to identify possible driving factors for the implementation of hydropower. Thus, the first set of inclusion and exclusion criteria were defined, with a broad approach. At this stage, the language criterion included English and Spanish, excluding any other languages. Other exclusion criteria such as the date or length of the document were not deemed suitable for the study.

2 Sources selection: Databases and other sources;

According to these criteria, the next step was the selection of sources. On the one hand, the most relevant scientific databases within the environmental and engineering fields were selected to search the academic and scientific literature (peer-reviewed journal papers and academic or research reports). The chosen databases were: ASCE Library, Dialnet, Riunet, ScienceDirect, Scopus, Springer Link, Taylor & Francis Online, Web of Science, Wiley Online Library, IEEE Xplore, Google Scholar.

3 Search strings definition: Selection and combination of keywords;

To perform the search in the selected databases, several combinations of the following keywords were employed, using appropriate Boolean search terms to combine them: “wastewater treatment plant”, “WWTP”, “wastewater resource recovery facility”, “WRRF”, “sewage treatment plant”, “STP”, “wastewater”, “sewage”, “energy”, “renewable energy”, “energy generation”, “energy recovery”, “energy self-sufficient*”, “hydropower”, “turbine”.

4 Documents analysis: Screening of retrieved documents and data extraction;

As a result of a first screening of the retrieved documents, some feedback was introduced in the methodology. It was noticed that several of the articles dealt with feasibility studies, which were merely theoretical or experimental applications of the technology. Thus, being a real case study was added to the inclusion criteria and all the feasibility studies were excluded. Besides, applying a snowball method and examining the references in the early stages of the search, it was observed that Switzerland and Korea were the leading countries in the number of published case studies. Therefore, the inclusion criteria and search keywords were extended to German and French languages and searches within the additional database KCI-Korean Journal Database were performed. Additionally, to seek for energy data from each identified case study, the name of the plant or location was also used as a keyword and most recent data were preferred.

5 Data synthesis;

Finally, the obtained data were extracted and analyzed using Microsoft Excel. The same worksheet was used for the synthesis of data and for the calculations of the selected KPIs, which is detailed next. Additionally, for the analysis of results, which will be displayed in Section 3.

2.2. Energy KPIs. Selection

In the final steps of the previous phase, for each WWTP identified as a real case study of hydropower application, the search was extended seeking published data about their general energy performance. In this phase, these data were further analyzed to establish a proper indicator to enable a comparison and the interpretation of results for the aim of the study.

As mentioned in Section 1, the energy issue at wastewater systems needs to be tackled in two parallel lines, improving energy efficiency and renewable energy technologies implementation [25].

Different parameters are involved in energy efficiency. Concerning electric energy consumption at a plant level, the first value to consider is the electricity consumed per unit of time ($kWh_{consumed}$/day and $kWh_{consumed}$/year). From these data, several authors have proposed indicators relative to the treated wastewater. The most commonly used quantitative indicator is kWh electric energy consumption/m^3 treated wastewater [12,17,66]. However, if the pollution load or the efficiency of the process are considered, other energy consumption indicators are considered to be more suitable. These include indicators such as kWh/PE-year, where the PE term (population equivalent) is related to the pollutants load. In Europe, according to Directive 91/271/EEC, the PE can be defined as the organic load with a BOD_5 of 60 g of oxygen per day [12]. Particular indicators based on main pollutants removals are also used. These include specific KPIs considering organic matter removal, such as kWh/kg $BOD_{removed}$ or kWh/kg $COD_{removed}$ [12,17,66], nutrients removal, such as kWh/kg $N_{eliminated}$ [12,66] or suspended solids as kWh/kg $TSS_{removed}$ [12,17,66]. Nevertheless, some authors like Longo et al. [12] highlighted the convenience of considering a global KPI, which embraces the overall removal of these pollutants, like kWh electric energy consumption/kg pollution units removed. With a similar approach, the same authors developed further specific KPIs for the particular aim of improving energy efficiency at WWTPs, within the frame of the ENERWATER project [37].

All these KPIs might show a wide range of different values, depending on the effecting factors described in Section 1, such as the size of the plant or type of treatment [9,12,14], providing valuable information for improvement in the first line of action, energy efficiency.

Key Performance Indicators (KPIs) are a well-established method widely used nowadays in the management of all types of business activities and organizations [67]. Indicators can be established at micro-, meso-, or macro-level, depending on the system being measured. Hence, at micro-level, a single process, plant, or organization is measured to monitor and when possible, improve their performance, whereas at macro-level, a whole sector or region is monitored, as a basis for policies design [68].

Focusing on a WWTP as the system to be considered at a micro-level, and the wastewater sector and wastewater management strategies from a region or country, as the system at a macro-level, some specific energy KPIs can be found in previous studies. Thus, the aim of this second phase was to determine which energy KPIs at a micro-level could complete the framework to provide useful indicators at a macro-level. These indicators might offer valuable information to be regarded in future planning strategies or to be included in benchmarking or decision-making management tools within the wastewater sector.

Several KPIs have already been defined in the literature to evaluate energy performance at WWTPs. The energy KPIs reviewed in this stage to consider their possible application to the case studies found, are summarized in Table 1.

Table 1. Main KPIs defined in the literature for energy performance monitoring at WWTPs.

Energy KPI Definition	Units	Source
Volume of Wastewater		
Electricity consumed/Volume treated wastewater	kWh/m^3	[12,17,66]
Pollution Load		
Electricity consumed/Population equivalent	kWh/PE-year	[12]
Electricity consumed/Biodegradable organic matter removed	kWh/kg BOD	[12,17,66]
Electricity consumed/Total organic matter removed	kWh/kg COD	[12,17,66]
Electricity consumed/Nutrients removed	kWh/kg N [1]	[12,66]
Electricity consumed/Total suspended solids removed	kWh/kg TSS	[12,17,66]
Electricity consumed/Global pollution removed	kWh/kg PU	[12]
Renewable Energy Generation		
(Total electricity production from renewable sources/Electricity consumed) × 100 [2]	%	[26,37,39,66]
(Electricity production from hydropower/Electricity consumed) × 100 [3]	%	[26]

[1] Nutrients usually include Nitrogen or Phosphorus separately. [2] Energy self-sufficiency (%): Ratio (annual electricity generated with renewable technologies/annual WWTP consumption) × 100. [3] Hydropower contribution (%) to energy self-sufficiency.

For the second line of action, renewable energy generation, at sites where there is simultaneously a recovery or generation of energy from renewable sources, additional indicators can be considered. Similarly, to consumption, energy production per unit of time is the most basic KPI, defined as $kWh_{generated}$/day or $kWh_{generated}$/year [12,66]. Electric and thermal energy are usually considered separately, and for the purpose of this study, only electricity is considered.

When merging both basic data (electricity consumed and electricity generated per unit time), another KPI can be defined, electric energy self-sufficiency [26,37,39,66]. The ratio (total renewable electric energy production/total electric energy consumption) × 100%, also called energy independence [26] or carbon neutral efficiency [16,36,39], was introduced in recent years, as an indicator directly related to the sustainability of a WWTP [28].

In [66], this KPI at the micro-level is also related to a global self-sufficiency index (in this case, including both, electric and thermal energy) at a regional level. As their research showed, this kind of indicator is ultimately used in decision support systems based on sustainability principles, which highlights their strategic relevance.

The research conducted in 2013 by Chae and Kang [26] studied the performance of a combination of experimental renewable energy generation systems installed at WWTPs. In the particular case tested, Kiheung Respia WWTP in Yongin (Korea), the electricity generation technologies applied as a pilot project were solar (photovoltaic) and small hydropower. In this study, the individual contribution of each technology to the self-sufficiency index was also calculated. Even though the obtained values for both were very low (2.05 and 0.75%, respectively), the main conclusions drawn by these authors [23,26] were that there is no single technology leading to energy self-sufficiency and that hybrid solutions need to be explored.

There are other indicators, such as those applied within the energy framework [28], which can provide more complete and detailed information, as they integrate energy with other aspects. Those indicators are very useful for a holistic approach. However, for the main purpose of this research, the latter two mentioned KPIs, seemed to be the most suitable indicators. Thus, the total energy self-sufficiency, including all renewable technologies for electricity generation applied at a particular site, and the particular contribution of hydropower, both as a percentage of total electricity consumption as defined above, were selected to be applied in this study.

3. KPIs Applied to Real Case Studies

3.1. Hydropower Application to Wastewater Systems: Real Case Studies

Following the methodology described in the previous section, in this study, a total of 36 existing real case studies of hydropower application to wastewater systems were found worldwide, in 12 different countries. As it was already noticed during the search, and it is shown in Figure 1, there are clearly 2 leading countries in the number of sites applying this technology, Switzerland and Korea, with 10 and 11 case studies, respectively.

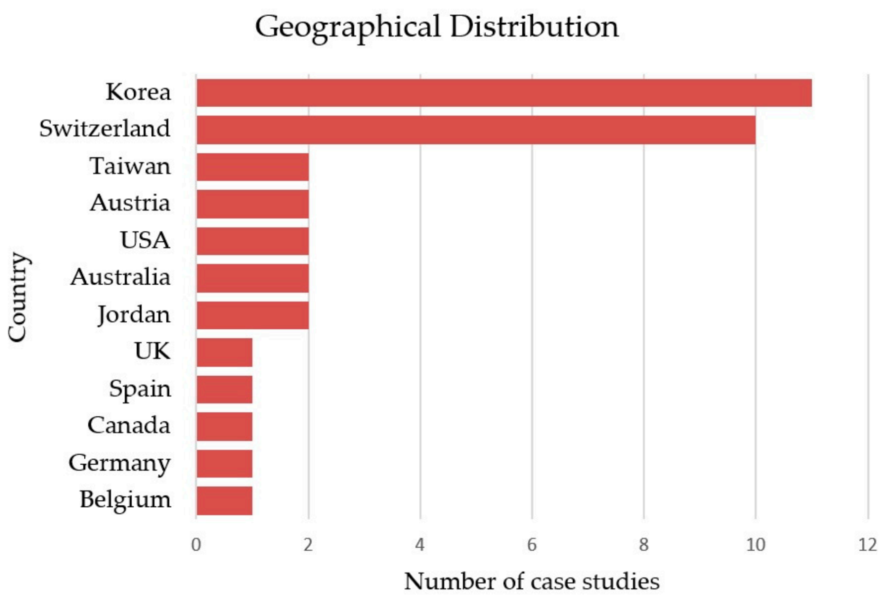

Figure 1. Geographical distribution, number of hydropower case studies found per country/district.

Table 2 shows the details of the 36 cases found. They are grouped by country/district including the name of the wastewater treatment plant, location, the year of the hydropower system installation, and source.

The first thing to notice, as shown in Figure 1 and Table 2, was the number of existing case studies found, compared to those included in previous peer-reviewed papers, that also analyzed the application of hydropower to WWTPs [20,21,52]. A total of 36 cases were identified, whereas the research carried out in 2017 by Bousquet et al. [20] included only 17 of these plants to develop their methodology. In [52], up to 9 particular cases are mentioned but their research was conducted before 2014 and the aim of that study was very specific. Other authors included even fewer hydropower sites in their studies, but most of those articles are complete reviews of several technologies for resources and energy recovery at WWTPs, and the hydropower cases are merely mentioned as examples of the technology [17,21].

Table 2. Real cases studies of hydropower application to wastewater systems found in the search. Renewable energy generation technologies used on-site and KPI values of total energy self-sufficiency (%) in case studies with available data.

Country/District	Name of WWTP	Location	Year	Renewable Energy Technologies [4]	% Self-Suff. [4]	Source
Austria	Plobb -Seefeld [1]	Seefeld Zirl	2005	H	>100%	[47]
	Ebswien	Vienna (Simmering)	2009, 2013 [2]	H + S + W [5]	11% [7]	[47]
Switzerland	Chaux-de- Fonds [1]	La Chaux-de-Fonds	2007, 2016 [2]	H + BCHP	65%	[69]
	Le Châble Profray	Val de Bagnes, station Verbier (Valais)	1993, 2008 [2]	N/A N/A	N/A N/A	[20]
	La Douve 1	Aigle, Leysin (Vaud)	1989, 2000 [2]	N/A	N/A	[20]
	La Douve 2	Aigle, Leysin (Vaud)	2001	N/A	N/A	[20]
	L'Asse [1]	Nyon (Vaud)	1990	H + BCHP + S	66.1% [7]	[20]
	Grächen	Grächen (Valais)	2011	N/A	N/A	[20]
	Engelberg	Engelberg	2010	H + BCHP [6] + S	>100% [7]	[20]
	Morgental (Hofen) [1]	Steinach (St. Gallen)	1916, 2014 [2]	H + BCHP [6] + S + W + T	>100% [7]	[20]
	Aïre	Genève	before 2015 [3]	H + BH	N/A	[20]
	La Louve [1]	Lausanne	2006	N/A	N/A	[52]
Germany	Emmerich (TWE)	Emmerich am Rhein	2000	H + BCHP	N/A	[20]
UK	Esholt	Bradford (Yorkshire)	2009	H + BCHP	>100%	[20,52]
Spain	Sur	Getafe (Madrid)	before 2014 [3]	H + BCHP	91.2%	[70]
Belgium	Brussels-North	Brussels	before 2019 [3]	H + BCHP + S + T	30%	[71]
Australia	North Head	Sydney	2010	H + BCHP	58%	[20,52,72]
	Gippsland Water Factory [1]	Maryvale (Gippsland, Victoria)	2010	H + BCHP	40%	[73]
Jordan	As samra	Amman City	2008	H + BCHP	80%	[20,47]
	As samra II	Amman City	2015	N/A	N/A	[20]
Korea	Asan	Chungnam asan	2000	N/A	N/A	[74,75]
	Cheonan	Chungnam cheonan	2002	N/A	N/A	[74,75]
	Jinhae	Gyeongnam jinhae	2004	N/A	N/A	[74,75]
	Shinshun	Daegu	2005	N/A	N/A	[74,75]
	Seoksu	Gyeonggi Anyang	2007	N/A	N/A	[74]
	Seobu	Daegu	2010	H + S	N/A	[75]
	Chungju	Chungju	2011	N/A	N/A	[75]

Table 2. *Cont.*

Country/District	Name of WWTP	Location	Year	Renewable Energy Technologies [4]	% Self-Suff. [4]	Source
	Nan Ji	Seoul	2014	H + BCHP + S + T	51.6% [8]	[76]
	Tan Chun	Seoul	before 2017 [3]	H + S + T	51.6% [8]	[77]
	Joong Rang	Seoul	2015	H + BCHP + S	51.6% [8]	[77]
	Seo Nam	Seoul	2015	H + BCHP + S + T	51.6% [8]	[77]
Taiwan	N/A	Taichung	before 2008 [3]	N/A	N/A	[20]
	Hsinchu	Hsinchu	before 2008 [3]	N/A	N/A	[20]
USA	Deer Island	Boston (Massachusetts)	2001	H + BCHP + S + W	26%	[20,47,52]
	Point Loma	San Diego	2001	H + BCHP	>100%	[20,52]
Canada	Clarkson	Mississauga	2015	H + BCHP	30.8% [7]	[78]

[1] Hydropower inlet flow or electricity output out of the boundary limits of the WWTP. [2] Year installation, last update. [3] "Before year": According to the date of the first reference found about that existing case study. [4] Abbreviations. H: Hydropower; BCHP: Combined heat and power from biogas; BH: Biogas for heat generation; S: Solar, photovoltaic; W: Wind; T: Thermal, heat recovery or generation (technology other than biogas). N/A: Not available. [5] CHP installation planned in the near future, which is expected to increase significantly total self-sufficiency. [6] CHP using some specific wastes as cosubstrate to enhance biogas generation. [7] Value calculated applying KPI definition (annual electricity generated with renewable technologies/annual consumption) $\times$ 100%. [8] Global value provided in the literature for the 4 WWTPs in Seoul altogether.

One remarkable issue is the geographical distribution. Firstly, the number of cases and year of installation observed in Switzerland and Korea, which also arose during the search. The first findings clearly pointed to them as what could be considered the leading countries. The driving forces include a favorable topology in Switzerland [20,47] and strong policies aiming for decarbonization of the energy system, especially remarkable for the WWT sector in Korea [26]. However, whereas Switzerland is usually regarded in the literature as the pioneer country for this application [20,47], the Korean experience has received little attention in previous works.

Another important result about the geographical distribution was the demonstration of an interest for the technology almost worldwide [20,21,23,47,48,52,79]. Regarding this, it is important to remark that the sites shown in Table 2, are only the real cases found following the described methodology. Actually, considering the difficulties found in the process of identifying all these case studies, due to the disaggregation of information and data, it is likely that there could be other cases with scarce or no publicly available information so far [80]. All this shows one of the main constraints encountered during this research: The lack of publicly available data in most cases, to endorse actual energy performance of these installations throughout the years [20,47,52,79]. Similar limitations within the wastewater sector were already reported by Strazzabosco [80].

Looking back at Table 2, out of Switzerland, where usually the topology provided high available head, it can be observed that many cases are located in big cities [20,47,52,71,77]. This could be due to two possible reasons. The first obvious one is that these plants are larger, a higher flow rate generates more power, and therefore higher is the economic feasibility in absolute terms too [20,52]. However, even though energy benchmarking studies have proven that the economy of scale is generally applicable, provided the process, and other circumstances are similar [10,16,36] in those cases the energy consumption also increases, and the differences for the values of the KPI considered here might not be so significant. Nevertheless, this cannot be confirmed due to the lack of energy data for a number of the cases studied, particularly, for the smaller plants [20,47,52,69]. Another possible reason could be related to the availability of specialized management resources in larger plants, as usually happens in industrial organizations [67,81–83]. This could also explain the fact that most of the plants have several renewable technologies installed. Awareness of the possibilities and access to knowledge play a crucial role in new technologies implementation, particularly, for a not well-known solution like hydropower [62,63].

Apart from the real case applications summarized in Table 2, on the one hand, several feasibility studies were also found during the search. As described in the previous section, these studies were excluded, as it could not be confirmed that they were existing real cases up to date. For example, some hydropower systems were installed as pilot trials in demonstrative projects, like the previously mentioned Kiheung Respia WWTP (Korea) in 2013 [23,26,75], and more recently, Zeekoegat WWTP in South Africa [79] or Stonecutters Island STW in Hong Kong [84]. Some other cases, which imply a foreseen implementation in the future, were also found, but they are not installed yet.

On the other hand, during the search, a couple of other cases were encountered, where the most updated information confirmed the removal of the systems after a few years of their installation. This is the case, for example, for the sewage system in Aachen (Germany) [85].

Nonetheless, all these studies, regardless of the final result, illustrate a worldwide interest in the possible application of this technology to wastewater systems. A deeper analysis of their performance, both in successful, but also in unsuccessful cases, would provide valuable information for future developments, with global applicability too.

Another issue observed during the screening of documents was that some cases were mentioned in the literature with different names. In this way, either the name of the plant, either the location, or any other denomination related with the site were used in different sources, when referring to the same case. One example of this was the Le Châble Profay plant, in Val Bagnes, canton Valais, which is the WWTP (STEP in French) treating the sewage from the Verbier ski resort. This case is referred to in some sources as Le Châble Profay [20] or just Profay [52], in others as Bagnes [21] and even as Verbier. Thus, for a clearer identification, the name and location data in Table 2 include all related terms used to cite a single case in the different sources reviewed.

This situation was frequently related to sites with particular or unusual configurations. That means that they represent cases in which the hydropower inlet flow and/or the electricity output from the turbine, enters or exits out of the boundary limits of the WWTP considered. This situation was found in 6 of the sites.

The case of Seefeld Zirl is the classic example already cited in previous works [47,52]. To reach the discharge point in the Inn River, after the treatment, the effluent from the WWTP has to be pumped over a hill. Then, the treated wastewater is discharged, and the available head at this point, 6 times greater than the hill elevation, is harnessed to generate electricity with a turbine.

Another example is the case Hofen–Morgental. Up to the last decade, these two municipalities had separated WWTPs. However, since 2014, they share the updated facilities at Morgental, and at the pressurized pipeline connecting the sewage from Hofen, a turbine was installed to generate electricity [20].

The cases of La Louve or Gippsland are remarkable too [52,73]. In those sites, multipurpose schemes were designed, interacting with nearby waterbodies for hydropower generation. The Gippsland case is simultaneously a good example of a circular economy applied to the water itself [73].

All these examples illustrate how useful would be for policy makers and wastewater managing stakeholders to be completely aware of the available possibilities in the planning and decision-making processes. This also highlights the importance of broadening the approach, and identify driving factors for hydropower implementation, other than economic feasibility.

Concerning the year of installation, in those cases where there have been updates adding turbines or changing the original ones, both dates have been included in Table 2. If the year of installation was not available, it is displayed as "before" the year of the first reference found for that case.

To better appreciate the temporal evolution, the years of the first installation of hydropower for all these cases were also plotted. As the objective was to obtain a global view, they were grouped into five-year periods. This is shown in Figure 2, where it can be observed that this evolution seems to be rather slow. According to this, six hydropower systems were already installed two decades ago and at least 34 of the 36 identified cases were working before 2016. Bearing in mind that for the cases with no year of installation confirmed in the literature (marked as "before" in Table 2), the real date could be even earlier, this means that about 90% of the hydropower systems would have been working for more than 5 years.

Even though there is an obvious time lapse since other previous studies were conducted, observing the year of installation data in Table 2, also plotted in Figure 2, it can be noticed that at least 25 systems were already running before 2011. Therefore, although all the previous publications provided important information for this research, these results seem to confirm that, to have a more complete framework, a broader approach to update the state of the art was needed.

Moreover, although it might be deemed that the technology is starting to be applied to wastewater systems in most recent years, this perception might not be completely accurate as can be observed in Figure 2. As it was already mentioned, according to the data, about 90% of the identified cases would have been working for more than 5 years.

This distribution of the year of installation shown in Figure 2 was another important finding. Together with the number of existing plants, this would imply that the accumulated experience in the application of this technology may be greater than assumed. A deeper analysis of that existing experience would allow to assess more accurately its current performance and therefore, its future potential.

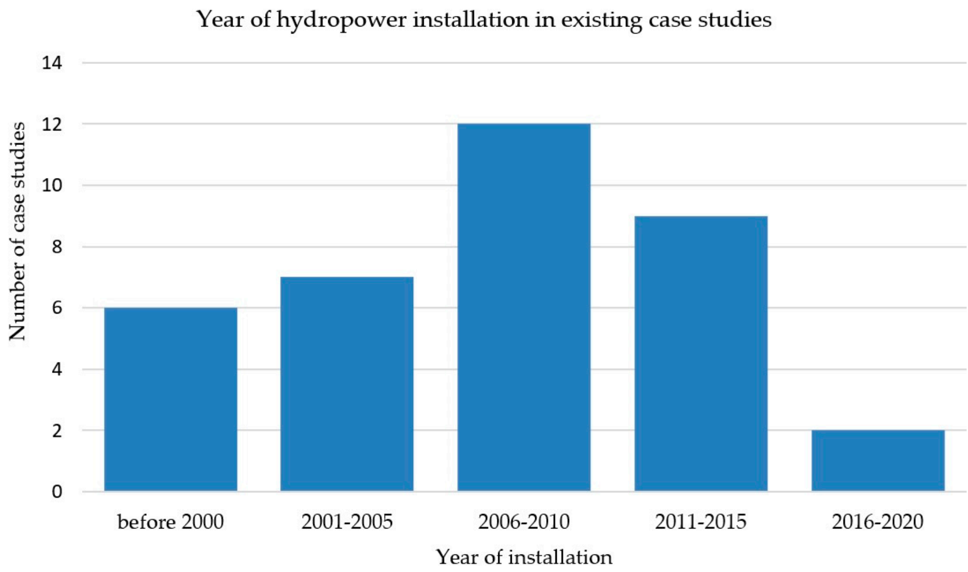

Figure 2. Distribution of the number of hydropower case studies per year of installation (grouped in a five-year period).

The search for publicly available data about energy for each particular plant, as explained in the previous section, additionally provided some specific information about their energy profile.

3.2. Energy Self-Sufficiency and Hydropower Contribution at WWTPs: Energy Profiles

After analyzing the gathered information, it was found that, for almost two-thirds of the cases (22 out of 36), there was published information about the technologies used on-site for energy generation (both, electric, and thermal). Besides, for half of the plants (19), the total energy self-sufficiency KPI as defined in Section 2 was either directly indicated in the literature, or easily computed according to that definition, from their total electricity consumption and generation data. These results are also summarized in Table 2.

From the energy data shown in Table 2, it can also be observed that 17 of the 22 cases, with publicly available information about their renewable energy generation, use both hydropower and biogas CHP (combined heat and power generation). In a few of these cases, some other technologies are applied as well. Just one plant uses hydropower as the only renewable technology. However, it is likely that the proportion of these cases would be different if updated data from all 36 plants were available.

Regarding other technologies, there are 11 plants with solar systems installed. One of them combined with hydropower only, and the rest combining hydropower and other technologies. In three of those, wind generation is used too. Those cases where there is a heat recovery or generation other than using biogas are indicated as "thermal".

Only in a few cases over 100% self-sufficiency is achieved, usually as a result of a combination of several technologies, particular configuration designs, and/or additional inputs from out of the boundary limits (for example, CHP using external cosubstrates for enhanced biogas generation).

Focusing now on the energy data, this was another important finding. As shown in Table 2, in most of the cases where data about the energy profile were available, biogas CHP or other renewable technologies like solar were also used at the site. This suggests that self-sufficiency is not a matter of technology choice, but a proper selection of the most suitable combination in each case. Not a matter of which technology should prevail, but an attitude towards continuously improving energy performance with a global perspective. The best results are usually achieved when integrating other possible inputs or interacting with the surrounding environment. None of the renewable energy technologies should exclude the others to be considered too. In this context, future research and further development of projects to optimize the design of hybrid solutions are needed.

Concerning the specific data for the hydropower indicator, only in 6 case studies the actual value of the contribution from this technology to their energy self-sufficiency was found directly published. These figures are shown in Table 3.

Table 3. KPI values of hydropower contribution to energy self-sufficiency in case studies with available data.

Country	Name of WWTP	% Self-Sufficiency	% Hydropower [2]
Austria	Plobb-Seefeld [1] Ebswien	>100% 11.0%	>100% 2.6%
Switzerland	L'Asse [1] Engelberg	66.1% [3] >100% [3]	33.9% [4] 65.0% [4]
UK	Esholt	>100%	5.0%
Spain	Sur	91.2%	2.1% [4,5]
Belgium	Brussels-North	30.0%	18.0%
Jordan	As samra	80.0%	24.0%
USA	Deer Island	26.0%	4.0%
Canada	Clarkson	30.8% [3]	1.3% [4]

[1] Hydropower inlet flow or electricity output out of the boundary limits of the WWTP. [2] Hydropower contribution (%) to energy self-sufficiency. [3] Value calculated applying KPI definition (annual electricity generated with renewable technologies/annual consumption) × 100%. [4] Value calculated applying KPI definition (annual electricity generated with hydropower/annual consumption) × 100%. [5] Values used for calculations correspond to different years.

Alike the global indicator, after searching for all publicly available energy data for each plant, for a few more cases it was possible to compute the value according to the specific KPI definition. Therefore, in those sites, where annual electricity consumption and annual electricity generation-specific from hydropower were available, the percentage of hydropower contribution was calculated. The obtained values in such cases are also displayed in Table 3. With that, still for only 10 of the case studies, both KPIs are available. To enable the comparison of results between the two KPIs and among the different facilities, the values for both indicators were plotted as shown in Figure 3.

Concerning the specific hydropower contribution to energy self-sufficiency, the limitation of available data was even stronger [20,80]. Nevertheless, some important conclusions can also be drawn from the obtained results.

Firstly, in Table 3 and Figure 3, it can be seen that the values are very heterogeneous. This can be due to some reasons. For example, technical differences affecting the calculation itself, such as the plant configuration, the facilities or equipment considered within the boundary limits of the system, the capacity of the plant, or the treatment processes involved [20,47,52,70,71,78]. Consequently, for a specific site, changing conditions in any of these factors could give different results too. In addition, due to strategic reasons, when hydropower contribution might have been low from a technical or economic point of view, but not regarded negligible from a sustainable perspective. Thus, either as the main energy recovery technology like in Engelberg (65%) [20] or only with a small contribution like in Clarkson (about 1%) [78], in any scenario, pondering on the possible implementation of hydropower could be of interest on the pathway towards self-sufficiency. In any case, these KPIs are valuable for performance monitoring and sustainability improvement, both individually and in aggregated evolution data [66–68].

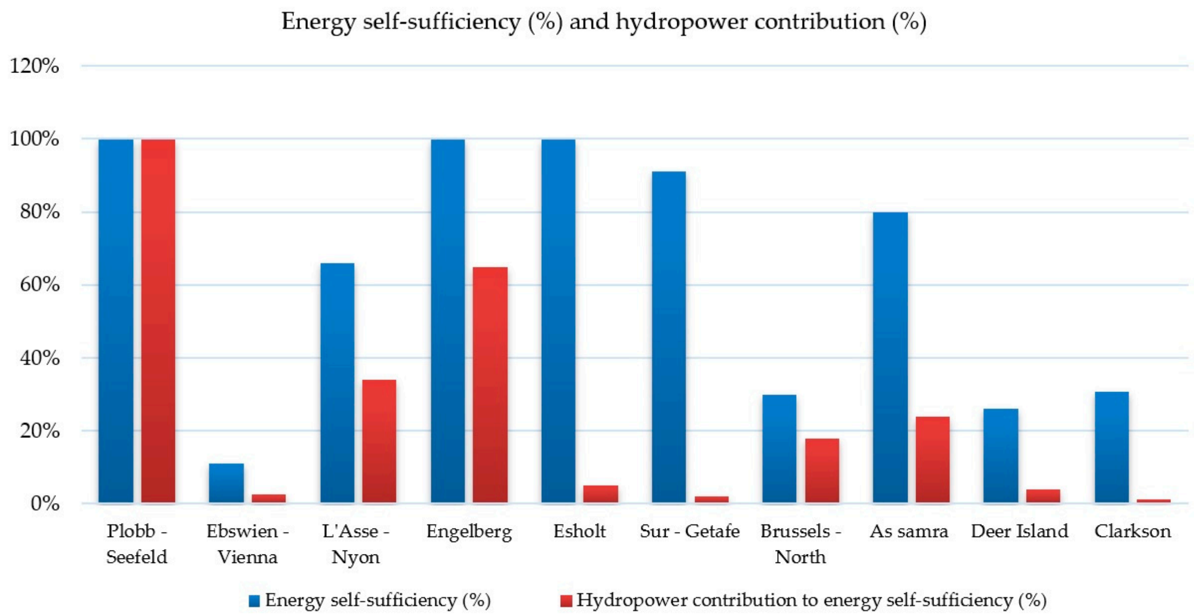

Figure 3. Energy KPI values obtained for case studies analyzed: % Total self-sufficiency (blue bar) considering all renewable energy technologies applied and % individual contribution of hydropower to self-sufficiency (red bar).

Secondly, in the cases where there is exchange out of the boundary limits, the significance of the KPIs varies [20,47,52,73]. In those particular cases, meaningful comparisons with any other sites are difficult to make. Nevertheless, as energy performance indicators, the KPIs here selected are still useful in any situation for self-comparison in time.

In some of the theoretical feasibility studies found during the search, these KPIs were also calculated, showing again a wide range of values. For WWTP Bottrop in Germany, a 73.4% total self-energy and a 0.9% contribution from hydropower were indicated in 2013 by Berger et al. [85]. Other examples of the possible contribution of hydropower to plant self-sufficiency were estimated for Juru Regional STP in Malaysia with 0.7% [55] or Tatlar WWTP in Turkey with up to 34% potential [54].

All these results illustrate the limitations of establishing a single value to determine the potential for the sector in a general way.

Current WWTPs are dynamic organizations, with the need to adapt to a changing context, like many industrial businesses do [81,82]. However, the limitations of budget can often hinder their investments with higher restrictions than in the private sector, especially for smaller plants [13,82,83]. However, awareness of the technology, demand, and costs are interrelated factors. If disclosure is increased and more affordable and reliable machinery is developed, hydropower might even be regarded as "low-hanging fruit," as energy efficiency measures in general already are [86], i.e., easy to identify and implement. This would enable managers of small wastewater systems to set achievable targets rather than attempting more sophisticated strategies [63,82,87]. It may pose an even more attractive option in those situations where new investments are extremely limited or important modifications of the treatment process or facilities present too high risks or constraints, as in the smaller wastewater systems [12,63,87]. This could also be the case in developing countries or in periods of uncertainty. Furthermore, this study is solely focused on wastewater systems, but surely improving small hydropower technologies might be of great interest in the water sector in general. Further research would allow to ascertain the range of possibilities that the technology could offer and the limitations for its application [20,21,52].

Wastewater treatment needs and increasing water quality demands are global issues. Nowadays, water policies in most countries trend to centralized systems [21], but more recently, some studies have pointed the convenience of shifting back to decentralized designs [10,88–91]. In either case, different scale of hydropower solutions could cover the full range of needs. If water policies are orientated towards centralized systems, the possibility to recover some energy at some points of the wastewater system, as in the configurations aforementioned or the installation of larger hydropower systems, might be worthy to consider [52,79]. If trends point to decentralized systems, these imply smaller plants, with their inherent characteristics and limitations to implement renewable energies technologies. The main appeal of hydropower is its flexibility, accessibility, and worldwide application [26,48,52,72,79], without interfering in the treatment process itself and without the strict limitation of scale that other technologies do present [14,25,38,92,93].

4. Conclusions

In this research, a deep search of existing hydropower applications to WWTPs was conducted, applying a novel approach based on the sustainability concept. Bearing in mind its main purpose, the study proposed a methodology based on some key aspects. Firstly, the search process was broadened, and some feedback during the screening stage, to identify as many real case studies as possible. Secondly, instead of considering economic data, commonly used to assess hydropower potential in previous works, the study applied KPIs based on the energy self-sufficiency concept.

As a novelty, this paper presents a new approach, identifying driving forces for hydropower implementation at WWTPs, other than economic feasibility. Besides, considering the results, it can be concluded that a broader perspective was actually needed. As shown in Table 2, the number of identified case studies (36) was significantly larger than expected from previous academic studies. Further, the geographical distribution showed that there is a worldwide interest in this technology. The findings also confirmed that there is a lack of awareness within the wastewater sector, about the possibilities hydropower could offer. As the main limitation found during this research, there is little information publicly available about the performance of real case studies.

Concerning the analysis of the energy profiles also displayed in Table 2, the results confirmed conclusions from previous studies, indicating that there is not a standalone technology that can lead to 100% energy self-sufficiency. The specific results for hydropower in Table 3 also suggest that there is not a rule of thumb to determine whether its installation is feasible or not. Moreover, it would be very complicated to establish a single global potential for the sector. Even when this potential seems to be low, factors other than absolute generation capacity and economic feasibility should be considered. All the results point to the conclusion that, for each particular plant, the options should be pondered according to its possibilities, from a technical, economic, and strategic point of view.

The main contribution of this research lies in its practical applicability, as it is focused on a deep analysis of case study applications, trying to learn from the real experience. In addition, the conclusion is that hydropower might deserve more attention. This technology could play a more important role in improving the sustainability of wastewater systems worldwide if efforts are made to tackle its current drawbacks and affordable machinery is developed. On the pathway towards energy self-sufficient WWTPs, hydropower is not likely to be the solution, but it could take part of it.

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References

1. Ament, J.; Freeman, R.; Carbone, C.; Vassall, A.; Watts, C. An Empirical Analysis of Synergies and Tradeoffs between Sustainable Development Goals. *Sustainability* **2020**, *12*, 8424. [CrossRef]
2. Coscieme, L.; Mortensen, L.F.; Donohue, I. Enhance environmental policy coherence to meet the Sustainable Development Goals. *J. Clean. Prod.* **2021**, *296*, 126502. [CrossRef]
3. Hegre, H.; Petrova, K.; Von Uexkull, N. Synergies and Trade-Offs in Reaching the Sustainable Development Goals. *Sustainability* **2020**, *12*, 8729. [CrossRef]
4. World Water Assessment Programme (United Nations), Wastewater: The Untapped Resource: The United Nations World Water Development Report 2017. Available online: https://unesdoc.unesco.org/ark:/48223/pf0000247153 (accessed on 7 April 2021).
5. Delanka-Pedige, H.M.K.; Munasinghe-Arachchige, S.P.; Abeysiriwardana-Arachchige, I.S.A.; Nirmalakhandan, N. Evaluating wastewater treatment infrastructure systems based on UN Sustainable Development Goals and targets. *J. Clean. Prod.* **2021**, *298*, 126795. [CrossRef]
6. Wang, X.; Liu, J.; Ren, N.-Q.; Yu, H.-Q.; Lee, D.-J.; Guo, X. Assessment of Multiple Sustainability Demands for Wastewater Treatment Alternatives: A Refined Evaluation Scheme and Case Study. *Environ. Sci. Technol.* **2012**, *46*, 5542–5549. [CrossRef]
7. Musabandesu, E.; Loge, F. Load shifting at wastewater treatment plants: A case study for participating as an energy demand resource. *J. Clean. Prod.* **2021**, *282*, 124454. [CrossRef]
8. Guerrini, A.; Romano, G.; Ferretti, S.; Fibbi, D.; Daddi, D. A Performance Measurement Tool Leading Wastewater Treatment Plants toward Economic Efficiency and Sustainability. *Sustainability* **2016**, *8*, 1250. [CrossRef]
9. Guerrini, A.; Romano, G.; Indipendenza, A. Energy Efficiency Drivers in Wastewater Treatment Plants: A Double Bootstrap DEA Analysis. *Sustainability* **2017**, *9*, 1126. [CrossRef]
10. Capodaglio, A.; Olsson, G. Energy Issues in Sustainable Urban Wastewater Management: Use, Demand Reduction and Recovery in the Urban Water Cycle. *Sustainability* **2019**, *12*, 266. [CrossRef]
11. Avilés, A.B.L.; Velázquez, F.D.C.; Del Riquelme, M.L.P. Methodology for Energy Optimization in Wastewater Treatment Plants. Phase I: Control of the Best Operating Conditions. *Sustainability* **2019**, *11*, 3919. [CrossRef]
12. Longo, S.; D'Antoni, B.M.; Bongards, M.; Chaparro, A.; Cronrath, A.; Fatone, F.; Lema, J.M.; Mauricio-Iglesias, M.; Soares, A.; Hospido, A. Monitoring and diagnosis of energy consumption in wastewater treatment plants. A state of the art and proposals for improvement. *Appl. Energy* **2016**, *179*, 1251–1268. [CrossRef]
13. Revollar, S.; Vilanova, R.; Vega, P.; Francisco, M.; Meneses, M. Wastewater Treatment Plant Operation: Simple Control Schemes with a Holistic Perspective. *Sustainability* **2020**, *12*, 768. [CrossRef]
14. Hanna, S.M.; Thompson, M.J.; Dahab, M.F.; Williams, R.E.; Dvorak, B.I. Benchmarking the Energy Intensity of Small Water Resource Recovery Facilities. *Water Environ. Res.* **2018**, *90*, 738–747. [CrossRef]
15. Wakeel, M.; Chen, B.; Hayat, T.; Alsaedi, A.; Ahmad, B. Energy consumption for water use cycles in different countries: A review. *Appl. Energy* **2016**, *178*, 868–885. [CrossRef]
16. Gu, Y.; Li, Y.; Li, X.; Luo, P.; Wang, H.; Robinson, Z.P.; Wang, X.; Wu, J.; Li, F. The feasibility and challenges of energy self-sufficient wastewater treatment plants. *Appl. Energy* **2017**, *204*, 1463–1475. [CrossRef]
17. Maktabifard, M.; Zaborowska, E.; Makinia, J. Achieving energy neutrality in wastewater treatment plants through energy savings and enhancing renewable energy production. *Rev. Environ. Sci. Biotechnol.* **2018**, *17*, 655–689. [CrossRef]
18. Guo, Z.; Sun, Y.; Pan, S.-Y.; Chiang, P.-C. Integration of Green Energy and Advanced Energy-Efficient Technologies for Municipal Wastewater Treatment Plants. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1282. [CrossRef] [PubMed]
19. Wang, H.; Yang, Y.; Keller, A.A.; Li, X.; Feng, S.; Dong, Y.-N.; Li, F. Comparative analysis of energy intensity and carbon emissions in wastewater treatment in USA, Germany, China and South Africa. *Appl. Energy* **2016**, *184*, 873–881. [CrossRef]
20. Bousquet, C.; Samora, I.; Manso, P.; Rossi, L.; Heller, P.; Schleiss, A.J. Assessment of hydropower potential in wastewater systems and application to Switzerland. *Renew. Energy* **2017**, *113*, 64–73. [CrossRef]
21. Diaz-Elsayed, N.; Rezaei, N.; Guo, T.; Mohebbi, S.; Zhang, Q. Wastewater-based resource recovery technologies across scale: A review. *Resour. Conserv. Recycl.* **2019**, *145*, 94–112. [CrossRef]
22. Ganora, D.; Hospido, A.; Husemann, J.; Krampe, J.; Loderer, C.; Longo, S.; Bouyat, L.M.; Obermaier, N.; Piraccini, E.; Stanev, S.; et al. Opportunities to improve energy use in urban wastewater treatment: A European-scale analysis. *Environ. Res. Lett.* **2019**, *14*, 044028. [CrossRef]
23. Chae, K.-J.; Kim, I.-S.; Ren, X.; Cheon, K.-H. Reliable energy recovery in an existing municipal wastewater treatment plant with a flow-variable micro-hydropower system. *Energy Convers. Manag.* **2015**, *101*, 681–688. [CrossRef]
24. Chen, K.-H.; Wang, H.-C.; Han, J.-L.; Liu, W.-Z.; Cheng, H.-Y.; Liang, B.; Wang, A.-J. The application of footprints for assessing the sustainability of wastewater treatment plants: A review. *J. Clean. Prod.* **2020**, *277*, 124053. [CrossRef]
25. Nakkasunchi, S.; Hewitt, N.J.; Zoppi, C.; Brandoni, C. A review of energy optimization modelling tools for the decarbonisation of wastewater treatment plants. *J. Clean. Prod.* **2021**, *279*, 123811. [CrossRef]
26. Chae, K.-J.; Kang, J. Estimating the energy independence of a municipal wastewater treatment plant incorporating green energy resources. *Energy Convers. Manag.* **2013**, *75*, 664–672. [CrossRef]
27. Qandil, M.D.; Abbas, A.I.; Salem, A.R.; Abdelhadi, A.I.; Hasan, A.; Nourin, F.N.; Abousabae, M.; Selim, O.M.; Espindola, J.; Amano, R.S. Net Zero Energy Model for Wastewater Treatment Plants. *J. Energy Resour. Technol.* **2021**, *143*, 1–38. [CrossRef]

28. Zhang, X.; Wei, Y.; Pan, H.; Xiao, H.; Wu, J.; Zhang, Y. The comparison of performances of a sewage treatment system before and after implementing the cleaner production measure. *J. Clean. Prod.* **2015**, *91*, 216–228. [CrossRef]
29. Smith, K.; Liu, S.; Liu, Y.; Guo, S. Can China reduce energy for water? A review of energy for urban water supply and wastewater treatment and suggestions for change. *Renew. Sustain. Energy Rev.* **2018**, *91*, 41–58. [CrossRef]
30. Velasquez-Orta, S.B.; Heidrich, O.; Black, K.; Graham, D. Retrofitting options for wastewater networks to achieve climate change reduction targets. *Appl. Energy* **2018**, *218*, 430–441. [CrossRef]
31. Mccarty, P.L.; Bae, J.; Kim, J. Domestic Wastewater Treatment as a Net Energy Producer–Can This be Achieved? *Environ. Sci. Technol.* **2011**, *45*, 7100–7106. [CrossRef] [PubMed]
32. Necibi, M.; Dhiba, D.; El Hajjaji, S. Contaminants of Emerging Concern in African Wastewater Effluents: Occurrence, Impact and Removal Technologies. *Sustainability* **2021**, *13*, 1125. [CrossRef]
33. Yan, P.; Qin, R.-C.; Guo, J.-S.; Yu, Q.; Li, Z.; Chen, Y.-P.; Shen, Y.; Fang, F. Net-Zero-Energy Model for Sustainable Wastewater Treatment. *Environ. Sci. Technol.* **2016**, *51*, 1017–1023. [CrossRef]
34. Longo, S.; Hospido, A.; Lema, J.M.; Mauricio-Iglesias, M. A systematic methodology for the robust quantification of energy efficiency at wastewater treatment plants featuring Data Envelopment Analysis. *Water Res.* **2018**, *141*, 317–328. [CrossRef] [PubMed]
35. Budych-Gorzna, M.; Szatkowska, B.; Jaroszynski, L.; Paulsrud, B.; Jankowska, E.; Jaroszynski, T.; Oleskowicz-Popiel, P. Towards an Energy Self-Sufficient Resource Recovery Facility by Improving Energy and Economic Balance of a Municipal WWTP with Chemically Enhanced Primary Treatment. *Energies* **2021**, *14*, 1445. [CrossRef]
36. Gandiglio, M.; Lanzini, A.; Soto, A.; Leone, P.; Santarelli, M. Enhancing the Energy Efficiency of Wastewater Treatment Plants through Co-digestion and Fuel Cell Systems. *Front. Environ. Sci.* **2017**, *5*. [CrossRef]
37. Longo, S.; Mauricio-Iglesias, M.; Soares, A.; Campo, P.; Fatone, F.; Eusebi, A.; Akkersdijk, E.; Stefani, L.; Hospido, A. ENERWATER–A standard method for assessing and improving the energy efficiency of wastewater treatment plants. *Appl. Energy* **2019**, *242*, 897–910. [CrossRef]
38. Ali, S.M.H.; Lenzen, M.; Sack, F.; Yousefzadeh, M. Electricity generation and demand flexibility in wastewater treatment plants: Benefits for 100% renewable electricity grids. *Appl. Energy* **2020**, *268*, 114960. [CrossRef]
39. Hao, X.; Liu, R.; Huang, X. Evaluation of the potential for operating carbon neutral WWTPs in China. *Water Res.* **2015**, *87*, 424–431. [CrossRef]
40. Del Río-Gamero, B.; Ramos-Martín, A.; Melián-Martel, N.; Pérez-Báez, S. Water-Energy Nexus: A Pathway of Reaching the Zero Net Carbon in Wastewater Treatment Plants. *Sustainability* **2020**, *12*, 9377. [CrossRef]
41. Guerra-Rodríguez, S.; Oulego, P.; Rodríguez, E.; Singh, D.N.; Rodríguez-Chueca, J. Towards the Implementation of Circular Economy in the Wastewater Sector: Challenges and Opportunities. *Water* **2020**, *12*, 1431. [CrossRef]
42. Lu, L.; Huang, Z.; Rau, G.H.; Ren, Z.J. Microbial Electrolytic Carbon Capture for Carbon Negative and Energy Positive Wastewater Treatment. *Environ. Sci. Technol.* **2015**, *49*, 8193–8201. [CrossRef]
43. Spriet, J.; McNabola, A.; Neugebauer, G.; Stoeglehner, G.; Ertl, T.; Kretschmer, F. Spatial and temporal considerations in the performance of wastewater heat recovery systems. *J. Clean. Prod.* **2020**, *247*, 119583. [CrossRef]
44. Schestak, I.; Spriet, J.; Styles, D.; Williams, A.P. Emissions down the drain: Balancing life cycle energy and greenhouse gas savings with resource use for heat recovery from kitchen drains. *J. Environ. Manag.* **2020**, *271*, 110988. [CrossRef]
45. Neugebauer, G.; Kretschmer, F.; Kollmann, R.; Narodoslawsky, M.; Ertl, T.; Stoeglehner, G. Mapping Thermal Energy Resource Potentials from Wastewater Treatment Plants. *Sustainability* **2015**, *7*, 12988–13010. [CrossRef]
46. Pérez-Sánchez, M.; Sánchez-Romero, F.J.; Ramos, H.M.; López-Jiménez, P.A. Energy Recovery in Existing Water Networks: Towards Greater Sustainability. *Water* **2017**, *9*, 97. [CrossRef]
47. Choulot, A.; Denis, V.; Punys, P. *Integration of Small Hydro Turbines into Existing Water Infrastructures In Hydropower-Practice and Application*; Hossein Samadi-Boroujeni, Ed.; Intech: Rijeka, Croatia, 2012.
48. Mitrovic, D.; Chacón, M.; García, A.; Morillo, J.; Diaz, J.; Ramos, H.; Adeyeye, K.; Carravetta, A.; McNabola, A. Multi-Country Scale Assessment of Available Energy Recovery Potential Using Micro-Hydropower in Drinking, Pressurised Irrigation and Wastewater Networks, Covering Part of the EU. *Water* **2021**, *13*, 899. [CrossRef]
49. McNabola, A.; Coughlan, P.; Williams, A.P. Energy recovery in the water industry: An assessment of the potential of micro-hydropower. *Water Environ. J.* **2013**, *28*, 294–304. [CrossRef]
50. Gallagher, J.; Harris, I.; Packwood, A.; Mc Nabola, A.; Williams, A. A strategic assessment of micro-hydropower in the UK and Irish water industry: Identifying technical and economic constraints. *Renew. Energy* **2015**, *81*, 808–815. [CrossRef]
51. Bekker, A.; Van Dijk, M.; Niebuhr, C.M.; Hansen, C. Framework development for the evaluation of conduit hydropower within water distribution systems: A South African case study. *J. Clean. Prod.* **2021**, *283*, 125326. [CrossRef]
52. Power, C.; McNabola, A.; Coughlan, P. Development of an evaluation method for hydropower energy recovery in wastewater treatment plants: Case studies in Ireland and the UK. *Sustain. Energy Technol. Assessments* **2014**, *7*, 166–177. [CrossRef]
53. García, A.M.; Díaz, J.R.; Morillo, J.G.; McNabola, A. Energy Recovery Potential in Industrial and Municipal Wastewater Networks Using Micro-Hydropower in Spain. *Water* **2021**, *13*, 691. [CrossRef]
54. Ak, M.; Kentel, E.; Kucukali, S. A fuzzy logic tool to evaluate low-head hydropower technologies at the outlet of wastewater treatment plants. *Renew. Sustain. Energy Rev.* **2017**, *68*, 727–737. [CrossRef]

55. Che Munaaim, M.A.; Zaw, T.; Ayob, A.; Md Sani, N.; Mydin, M.A.O. The Potential of Micro Hydro Generator Embedded at 100,000PE Sewerage Treatment Plant. *J. Adv. Res. Fluid Mech. Therm. Sci. J.* **2018**, *51*, 1–7. Available online: http://www.akademiabaru.com/arfmts.html (accessed on 1 April 2021).
56. Mauricio-Iglesias, M.; Longo, S.; Hospido, A. Designing a robust index for WWTP energy efficiency: The ENERWATER water treatment energy index. *Sci. Total Environ.* **2020**, *713*, 136642. [CrossRef] [PubMed]
57. Loderer, C.; Lesjean, B.; Krampe, J. PowerStep-Wastewater as Source of Biomass for Renewable Energy. In Proceedings of the EGU General Assembly Conference Abstracts, Vienna, Austria, 23–28 April 2017.
58. Saidan, M.; Khasawneh, H.J.; Aboelnga, H.; Meric, S.; Kalavrouziotis, I.; Jasem, A.S.H.; Hayek, B.O.; Al-Momany, S.; Al Malla, M.; Porro, J.C. Baseline carbon emission assessment in water utilities in Jordan using ECAM tool. *J. Water Supply Res. Technol.* **2019**, *68*, 460–473. [CrossRef]
59. Larriba, O.; Rovira-Cal, E.; Juznic-Zonta, Z.; Guisasola, A.; Baeza, J.A. Evaluation of the integration of P recovery, polyhydroxyalkanoate production and short cut nitrogen removal in a mainstream wastewater treatment process. *Water Res.* **2020**, *172*, 115474. [CrossRef] [PubMed]
60. Rodriguez, D.J.; Serrano, H.A.; Delgado, A.; Nolasco, D.; Saltiel, G. Shifting paradigms for smarter wastewater interventions in Latin America and the Caribbean. *Waste Resour.* **2020**. [CrossRef]
61. Alvarez, V.V.; Buchauer, K. East Asia and Pacific-Wastewater to Energy Processes: A Technical Note for Utility Managers in EAP Countries: Main Report (English). Washington, D.C.: World Bank Group. 2014. Available online: https://documents.worldbank.org/en/publication/documents-reports/documentdetail/489941468188683153/main-report (accessed on 11 April 2021).
62. Kretschmer, F.; Neugebauer, G.; Stoeglehner, G.; Ertl, T. Participation as a Key Aspect for Establishing Wastewater as a Source of Renewable Energy. *Energies* **2018**, *11*, 3232. [CrossRef]
63. Diaz-Elsayed, N.; Rezaei, N.; Ndiaye, A.; Zhang, Q. Trends in the environmental and economic sustainability of wastewater-based resource recovery: A review. *J. Clean. Prod.* **2020**, *265*, 121598. [CrossRef]
64. Neto, G.C.D.O.; Pinto, L.F.R.; Amorim, M.P.C.; Giannetti, B.F.; de Almeida, C.M.V.B. A framework of actions for strong sustainability. *J. Clean. Prod.* **2018**, *196*, 1629–1643. [CrossRef]
65. Adams, R.; Jeanrenaud, S.; Bessant, J.; Overy, P.; Denyer, D. *Innovating for Sustainability A Systematic Review of the Body of Knowledge*; Network for Business Sustainability: London, ON, Canada, 2012.
66. Palma-Heredia, D.; Poch, M.; Cugueró-Escofet, M. Implementation of a Decision Support System for Sewage Sludge Management. *Sustainability* **2020**, *12*, 9089. [CrossRef]
67. Villazón, C.C.; Pinilla, L.S.; Olaso, J.R.O.; Gandarias, N.T.; De Lacalle, N.L. Identification of Key Performance Indicators in Project-Based Organisations through the Lean Approach. *Sustainability* **2020**, *12*, 5977. [CrossRef]
68. Sánchez-Ortiz, J.; Rodríguez-Cornejo, V.; Del Río-Sánchez, R.; García-Valderrama, T. Indicators to Measure Efficiency in Circular Economies. *Sustainability* **2020**, *12*, 4483. [CrossRef]
69. Rueetschi, M. *Doubs Electricity. Hydroelectric Use of Water from the Sewage Treatment Plant and the Street Drains of the City of La Chaux-de-Fonds*; Technical report (No. SFOE–280087), Naturelec SA c/o Planair SA; 2008.
70. Lizarralde, I.; Fernández-Arévalo, T.; Manas, A.; Ayesa, E.; Grau, P. Model-based opti mization of phosphorus management strategies in Sur WWTP, Madrid. *Water Res.* **2019**, *153*, 39–52. [CrossRef] [PubMed]
71. Van Nuijs, A.L.; Mougel, J.-F.; Tarcomnicu, I.; Bervoets, L.; Blust, R.; Jorens, P.G.; Neels, H.; Covaci, A. Sewage epidemiology — A real-time approach to estimate the consumption of illicit drugs in Brussels, Belgium. *Environ. Int.* **2011**, *37*, 612–621. [CrossRef]
72. Radcliffe, J.C. The water energy nexus in Australia – The outcome of two crises. *Water Energy Nexus* **2018**, *1*, 66–85. [CrossRef]
73. Daigger, G.T.; Hodgkinson, A.; Aquilina, S.; Burrowes, P. Creation of a sustainable water resource through reclamation of municipal and industrial wastewater in the Gippsland Water Factory. *J. Water Reuse Desalination* **2013**, *3*, 1–15. [CrossRef]
74. Nah, D.H.; Lee, S.H. Feasibility Study on the Construction of Small Hydro-Power Plants in Gumi Sewage Treatment Plant Discharge Point. *J. Korean Soc. Water Wastewater* **2010**, *24*, 173–181.
75. Chae, K.-J.; Kim, N.-S.; Cheon, K.-H.; Kim, W.-K.; Kim, J.-Y.; Lee, C.-H.; Park, W.-S. Micro-Hydropower System with a Semi-Kaplan Turbine for Sewage Treatment Plant Application: Kiheung Respia Case Study. *J. Korean Soc. Environ. Eng.* **2013**, *35*, 363–370. [CrossRef]
76. Lee, S.-H.; Kang, H.-J.; Park, H.-D. Influence of influent wastewater communities on temporal variation of activated sludge communities. *Water Res.* **2015**, *73*, 132–144. [CrossRef]
77. Choing, J. Water Supply Services and their Future–Reliable, Sustainable and Smart. In Proceedings of the 11th International Symposium on Water Supply Technology, Yokohama, Japan, 9–11 July 2019.
78. Regional Municipality of Peel, Clarkson Wastewater Treatment Plant Annual Report 2019. Available online: https://peelregion.ca/wastewater/_media/clarkson-WWTP-annual-report.pdf (accessed on 13 April 2021).
79. Loots, I.; van Dijk, M.; Barta, B.; van Vuuren, S.; Bhagwan, J. A review of low head hydropower technologies and applications in a South African context. *Renew. Sustain. Energy Rev.* **2015**, *50*, 1254–1268. [CrossRef]
80. Strazzabosco, A.; Kenway, S.; Lant, P. Quantification of renewable electricity generation in the Australian water industry. *J. Clean. Prod.* **2020**, *254*, 120119. [CrossRef]
81. Tsvetkova, D.; Bengtsson, E.; Durst, S. Maintaining Sustainable Practices in SMEs: Insights from Sweden. *Sustainability* **2020**, *12*, 10242. [CrossRef]

82. Södergren, K.; Palm, J. How Organization Models Impact the Governing of Industrial Symbiosis in Public Wastewater Management. An Explorative Study in Sweden. *Water* **2021**, *13*, 824. [CrossRef]
83. Kaselofsky, J.; Rošā, M.; Jekabsone, A.; Favre, S.; Loustalot, G.; Toma, M.; Marín, J.D.; Nicolás, M.M.; Cosenza, E. Getting Municipal Energy Management Systems ISO 50001 Certified: A Study with 28 European Municipalities. *Sustainability* **2021**, *13*, 3638. [CrossRef]
84. Zhuang, H.; Guan, J.; Leu, S.-Y.; Wang, Y.; Wang, H. Carbon footprint analysis of chemical enhanced primary treatment and sludge incineration for sewage treatment in Hong Kong. *J. Clean. Prod.* **2020**, *272*, 122630. [CrossRef]
85. Berger, V.; Niemann, A.; Frehmann, T.; Brockmann, H. Advanced energy recovery strategies for wastewater treatment plants and sewer systems using small hydropower. *Water Util. J. EWRA* **2013**, *5*, 15–24.
86. Bergmann, A.; Rotzek, J.N.; Wetzel, M.; Guenther, E. Hang the low-hanging fruit even lower - Evidence that energy efficiency matters for corporate financial performance. *J. Clean. Prod.* **2017**, *147*, 66–74. [CrossRef]
87. Ling, J.; Germain, E.; Murphy, R.; Saroj, D. Designing a Sustainability Assessment Framework for Selecting Sustainable Wastewater Treatment Technologies in Corporate Asset Decisions. *Sustainability* **2021**, *13*, 3831. [CrossRef]
88. Hafeez, A.; Shamair, Z.; Shezad, N.; Javed, F.; Fazal, T.; Rehman, S.U.; Bazmi, A.A.; Rehman, F. Solar powered decentralized water systems: A cleaner solution of the industrial wastewater treatment and clean drinking water supply challenges. *J. Clean. Prod.* **2021**, *289*, 125717. [CrossRef]
89. Risch, E.; Boutin, C.; Roux, P. Applying life cycle assessment to assess the environmental performance of decentralised versus centralised wastewater systems. *Water Res.* **2021**, *196*, 116991. [CrossRef] [PubMed]
90. Johannsen, R.; Østergaard, P.; Maya-Drysdale, D.; Mouritsen, L.K.E. Designing Tools for Energy System Scenario Making in Municipal Energy Planning. *Energies* **2021**, *14*, 1442. [CrossRef]
91. Roefs, I.; Meulman, B.; Vreeburg, J.H.; Spiller, M. Centralised, decentralised or hybrid sanitation systems? Economic evaluation under urban development uncertainty and phased expansion. *Water Res.* **2017**, *109*, 274–286. [CrossRef] [PubMed]
92. Riley, D.M.; Tian, J.; Güngör-Demirci, G.; Phelan, P.; Villalobos, J.R.; Milcarek, R.J. Techno-Economic Assessment of CHP Systems in Wastewater Treatment Plants. *Environments* **2020**, *7*, 74. [CrossRef]
93. Di Capua, F.; Spasiano, D.; Giordano, A.; Adani, F.; Fratino, U.; Pirozzi, F.; Esposito, G. High-solid anaerobic digestion of sewage sludge: Challenges and opportunities. *Appl. Energy* **2020**, *278*, 115608. [CrossRef]