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HYDROPOWER POTENTIAL FOR ENERGY RECOVERY IN WASTEWATER SYSTEMS. ASSESSMENT METHODOLOGY AND PRACTICAL APPLICATION

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Abstract

The 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. However, these SDGs are not isolated goals, they can be interrelated. SDG 6 (Clean water and sanitation) includes targets that are also critical for achieving SDG 3 (Good health and well-being) or SDG 14 (Life below water). Nowadays the energy demand for wastewater treatment is very high and it is expected to increase even more in the next decade. Therefore, the performance of this industry will ultimately have an effect on SDG 7 (Affordable and clean energy) and SDG 13 (Climate action) too. In this context, it is necessary to apply the sustainability approach to wastewater systems to simultaneously achieve all these goals. More sustainable energy performance of wastewater treatment plants (WWTPs) implies two parallel steps. On the one hand, a reduction of energy consumption, by improving operational efficiencies of processes and facilities. On the other hand, by the implementation of renewable energy technologies on-site, aiming for energy self-sufficiency. In order to take action in the short term, existing mature technologies should be explored to evaluate their potential contribution to the decarbonization roadmaps in the wastewater industry. Hydropower might be one of these technologies.

The main objective of this thesis is to develop a methodology, addressed to wastewater governance stakeholders, to assess the potential of hydropower application to WWTPs, regarding all three dimensions of sustainability. According to this, the final aim of this study is to illustrate the practical possibilities, usually unknown to most of them, that hydropower could offer to the wastewater sector in the pathway towards more sustainable systems.

To achieve that aim, the steps followed during the three stages of this research included:

(i) Contextualization: The review of the state of the art was conducted in two parallel lines, about the energy needs for wastewater treatment and mature technologies for renewable energy generation, and about hydropower applied to recover energy from existing networks. In order to complete the current framework, this stage was extended with an exhaustive search of real case studies of hydropower applications to WWTPs, and an analysis of their energy performance. In this stage, 49 case studies were identified worldwide, and their energy data were extracted and analyzed.

(ii) Methodology development: In a preliminary step, existing methodologies for hydropower potential assessment addressed to governance stakeholders were analyzed and compared with the framework completed during the contextualization stage. As a result, a methodology with a broader approach was developed. First of all, it introduces the consideration of the decision-making level to select the scope of the study (a group of WWTPs). Then, the proposed methodology consists of two steps. In step 1 (technical assessment of hydropower potential) individual power output is estimated for each site of the group. In step 2 (global assessment), after analyzing existing guidelines in the area of study, a multi-criteria decision analysis (MCDA) method with sustainability criteria is defined. Alignment with the context is a key issue introduced in this proposal, in step 1 to determine the stakeholders involved in the decision-making process, and in step 2 to adapt the method and criteria to their real options.

(iii) Practical application: This stage completes the research with the application of both steps of the proposed methodology to a case study, a group of 186 WWTPs in the region of Valencia (Spain), selected according to their management model.

The results obtained throughout this research were published in 3 publications in JCR indexed journals.

The findings from the contextualization stage are included in *Publication I and II.* In *Publication I*, after examining the general background, energy self-sufficiency indicators were applied to the identified case studies, and their renewable energy profiles were analyzed. The results suggested that there is no rule of thumb to determine whether hydropower installation is feasible or not at a single plant. In *Publication II*, the technical data of the hydropower systems in the case studies were examined, and their energy generation and capacity factors were evaluated. This analysis indicated that improving machinery efficiency still poses a major challenge, particularly regarding the fluctuations in flow rate. The overall results of this stage showed that there is an existing experience that is not being used to explore hydropower as an option for energy recovery in the wastewater sector.

The proposed methodology is presented in *Publication II* (step 1, technical assessment) and *Publication III* (step 2, global assessment). In *Publication II* the process for individual technical assessment was validated with the data from real case studies obtained during the contextualization stage. Moreover, it was suggested to include possible driving factors in the decision process, other than economic feasibility, which is usually the only dimension considered in previous methodologies. Thus, the individual power to determine the cut-off point for a WWTP to be considered as a potential site was proposed to be adjusted according to technical feasibility. In *Publication III* the MCDA method is developed, based on the guidelines in the wastewater governance instrument in Spain (Plan for Wastewater Treatment, Sanitation, Efficiency, Savings and Reuse from the Spanish Ministry, known as PDSEAR). To select suitable criteria in the economic, environmental, and social dimensions, a questionnaire was elaborated with a range of applicable criteria, extracted from a specific review of MCDA studies in relevant applications.

Finally, in *Publication III* the complete methodology was applied to a group of 186 plants in the Region of Valencia, selected according to their management model. In step 1, based on technical feasibility, 34 potential sites were identified. For this group, the generation of electricity was estimated at 340,472 kWh/year. However, it was found that if some modifications of current discharge points were feasible, the potential could be higher than the given results, up to 37.5% in the analyzed sample. In step 2, based on the PDSEAR guidelines and the questionnaires, 10 sustainability criteria were defined, regarding all three dimensions. The results showed that the perspective may be different, if the outcomes from step 1, are put into context in step 2, with the application of the MCDA method. This research demonstrates that, in a sustainability framework, hydropower might be an interesting option to consider for the decarbonization of wastewater systems. Based on this study, decision-making stakeholders could directly design their own methodologies, adapted to the specific context.

Resumen

Los Objetivos de Desarrollo Sostenible (ODS) plantean un llamamiento global para conseguir la sostenibilidad en aspectos esenciales de la vida humana, como el hambre o la salud. Sin embargo, estos ODS no deben concebirse como una agenda de objetivos independientes, ya que varios de ellos están interrelacionados entre sí. El ODS 6 (Agua limpia y saneamiento) incluye metas que son a su vez críticas para la consecución del ODS 3 (Salud y bienestar) o el ODS 14 (Vida submarina). El consumo de energía actual para el tratamiento de aguas residuales es muy elevado, y todas las previsiones apuntan a un notable incremento de la demanda en la próxima década. De este modo, el desempeño energético de este sector tendrá también efectos en el ODS 7 (Energía asequible y no contaminante) y el ODS 13 (Acción por el clima). En este contexto, resulta necesario aplicar la perspectiva de sostenibilidad a los sistemas de saneamiento y tratamiento de las aguas residuales, para poder conseguir de forma simultánea todos estos objetivos. Un desempeño energético más sostenible de las Estaciones Depuradoras de Aguas Residuales (EDAR) implica acciones en dos líneas. Por una parte, reduciendo el consumo, a través de la mejora de la eficiencia energética de procesos e instalaciones. Por otra, mediante la implantación de tecnologías de generación de energías renovables en las propias EDAR, orientadas a aumentar su autoabastecimiento energético. Con el fin de poder implantar medidas a corto plazo, es necesario explorar las posibilidades que pueden ofrecer las tecnologías ya maduras en la actualidad, y evaluar su potencial contribución a la descarbonización del sector. La generación de electricidad mediante maquinaria hidráulica que aproveche la energía potencial de los efluentes podría ser una de ellas.

El principal objetivo de esta tesis doctoral consiste en desarrollar una metodología, dirigida a los agentes de gobernanza involucrados en la toma de decisiones, para evaluar el potencial de generación de energía hidráulica en EDAR, considerando las tres dimensiones de sostenibilidad. Así, el objeto final es ilustrar las posibilidades de aplicación de esta tecnología, actualmente poco conocida para el sector, que podría contribuir a una gestión más sostenible de las aguas residuales. Para conseguir dicho objetivo, las fases desarrolladas durante este trabajo de investigación incluyeron los siguientes pasos:

(i) Contextualización: Se revisó el estado del arte en dos líneas de investigación. Una sobre las necesidades energéticas para el tratamiento de aguas residuales y las tecnologías disponibles en la actualidad para la generación de energía renovable en EDAR. Otra en cuanto al estado de la tecnología para la recuperación de energía en redes de agua existentes mediante maquinaria hidráulica. Para completar el marco de contextualización, la revisión se amplió realizando una búsqueda exhaustiva de casos de estudio reales de aplicación de esta tecnología en EDAR. En esta fase se identificaron 49 casos de estudio a nivel mundial, y se analizó su desempeño energético.

(ii) Desarrollo de la metodología: Como paso previo se analizaron las metodologías existentes para evaluación del potencial de esta tecnología, dirigidas a agentes de gobernanza. El resultado de dicho análisis se comparó con la información obtenida sobre casos de estudio en la contextualización. Como resultado, durante esta tesis se ha desarrollado una metodología con una nueva perspectiva. En primer lugar, se introduce la necesidad de considerar el nivel al que se produce la toma de decisiones, para adaptar el alcance del estudio (grupo de EDAR gestionadas por un mismo agente). Una vez identificado el alcance, la metodología se desarrolla en dos etapas. En la etapa 1 (evaluación técnica) el potencial de generación de energía hidráulica se estima de forma individual para cada EDAR del grupo analizado. En la etapa 2 (evaluación global) se propone un método de decisión multicriterio introduciendo criterios de sostenibilidad, tras el análisis del contexto en la zona de estudio. La alineación de la metodología con su contexto de aplicación se considera una cuestión clave en esta propuesta. En la etapa 1, para la identificación de los agentes de gobernanza responsables de la toma de decisiones en las estrategias de descarbonización y definición del alcance. En la etapa 2, para adaptar la metodología y los criterios a las directrices existentes y a sus posibilidades reales de aplicación.

(iii) Aplicación práctica: Esta fase complementa el estudio con la aplicación de las dos etapas mencionadas a un caso práctico. Así, se muestra la aplicación de la metodología a un grupo de 186 EDAR de la Comunidad Valenciana (España), que comparten la misma modalidad de financiación.

Los resultados obtenidos a lo largo de este trabajo de investigación han sido publicados en 3 artículos de revistas indexadas (JCR).

Los resultados de la contextualización se publicaron en el *Artículo I* y el *Artículo II*. En el *Artículo I* se examinó el marco actual, y se aplicaron indicadores de desempeño a los casos reales, en base al concepto de autoabastecimiento con energías renovables. Los resultados ilustraron la dificultad para establecer una norma general para determinar la viabilidad de esta tecnología. En el *Artículo II*, se analizaron los datos de la maquinaria hidráulica instalada, la generación de energía y los factores de capacidad. Este análisis evidenció la necesidad de continuar con líneas de investigación para mejorar la eficiencia de la maquinaria hidráulica en esta aplicación, ya que las fluctuaciones de caudal típicas en las EDAR no permiten aprovechar actualmente el potencial existente al máximo. Los resultados de esta fase en general demostraron que existe una experiencia real en la aplicación práctica de esta tecnología que no se está utilizando para el desarrollo de todo su potencial en este sector.

La metodología propuesta se presentó en el *Artículo II* (etapa 1, evaluación técnica) y en el *Artículo III* (etapa 2, evaluación global). En el *Artículo II* se validó el método para la evaluación individual de potencial técnico, a partir del análisis de metodologías existentes y de los casos de estudio identificados en la contextualización. Se sugiere la necesidad de incluir en el proceso de decisión otras consideraciones, además de la viabilidad económica, que es el único criterio en las metodologías previas. Así, se propone que el límite para determinar la viabilidad se base exclusivamente en criterios técnicos conforme al estado del arte de la tecnología, en lugar de económicos. En el *Artículo III* se desarrolló el método de decisión multicriterio, basado en las directrices del instrumento de gobernanza para aguas residuales en España (Plan Nacional de Depuración, Saneamiento, Eficiencia, Ahorro y Reutilización, conocido como Plan DSEAR). Para la selección de los criterios en las tres dimensiones de sostenibilidad (económica, medioambiental y social), se elaboró un cuestionario con criterios aplicables en este contexto, extraídos tras una revisión de estudios de aplicación de métodos multicriterio en EDAR o energías renovables.

Finalmente, en el *Artículo III* se aplicó la metodología a un grupo de 186 EDAR de la Comunidad Valenciana. En la etapa 1 se identificaron 34 plantas con potencial técnico, estimando una generación de electricidad de 340,472 kWh/año. Como hallazgo de esta fase se observó la posibilidad de aumentar dicho potencial hasta un 37.5%, en caso de ser viables modificaciones de los puntos de vertido. En la etapa 2, en base al PDSEAR y los cuestionarios, se definieron 10 criterios, considerando las tres dimensiones de sostenibilidad. Esto mostró que, cuando los resultados de la etapa 1 se ponen en el contexto de sostenibilidad en la etapa 2, se obtiene una nueva perspectiva. Esta investigación demuestra que, en el marco de un desarrollo sostenible, la recuperación de energía hidráulica del agua residual podría ser una opción más en la descarbonización de este sector. Tomando como base esta propuesta, agentes de gobernanza para la gestión de aguas residuales en otro contexto podrían desarrollar metodologías similares adaptadas a su propio entorno.

Resum

Els Objectius de Desenvolupament Sostenible (ODS) plantegen una crida global per a aconseguir la sostenibilitat en aspectes essencials de la vida humana, com la fam o la salut. No obstant això, aquests ODS no han de concebre's com una agenda d'objectius independents, ja que diversos d'ells estan interrelacionats entre si. El ODS 6 (Aigua neta i sanejament) inclou metes que són al seu torn crítiques per a la consecució del ODS 3 (Salut i benestar) o el ODS 14 (Vida submarina). El consum d'energia actual per al tractament d'aigües residuals és molt elevat, i totes les previsions apunten a un notable increment de la demanda en la dècada vinent. D'aquesta manera, l'acompliment energètic d'aquest sector tindrà també efectes en el ODS 7 (Energia assequible i no contaminant) i el ODS 13 (Acció pel clima). En aquest context, resulta necessari aplicar la perspectiva de sostenibilitat als sistemes de sanejament i tractament de les aigües residuals, per a poder aconseguir de manera simultània tots aquests objectius. Un acompliment energètic més sostenible de les Estacions Depuradores d'Aigües Residuals (EDAR) implica accions en dues línies. D'una banda, reduint el consum, a través de la millora de l'eficiència energètica de processos i instal·lacions. Per una altra, mitjançant la implantació de tecnologies de generació d'energies renovables en les pròpies EDAR, orientades a augmentar el seu autoproveïment energètic. Amb la finalitat de poder implantar mesures a curt termini, és necessari explorar les possibilitats que poden oferir les tecnologies ja madures en l'actualitat, i avaluar la seua potencial contribució a la descarbonització del sector. La generació d'electricitat mitjançant maquinària hidràulica que aprofite l'energia potencial dels efluents podria ser una d'elles.

El principal objectiu d'aquesta tesi doctoral consisteix a desenvolupar una metodologia, dirigida als agents de governança involucrats en la presa de decisions, per a avaluar el potencial de generació d'energia hidràulica en EDAR, considerant les tres dimensions de sostenibilitat. Així, l'objecte final és il·lustrar les possibilitats d'aplicació d'aquesta tecnologia, actualment poc coneguda per al sector, que podria contribuir a una gestió més sostenible de les aigües residuals. Per a aconseguir aquest objectiu, les fases desenvolupades durant aquest treball de recerca van incloure els següents passos:

(i) Contextualització: Es va revisar l'estat de l'art en dues línies d'investigació. Una sobre les necessitats energètiques per al tractament d'aigües residuals i les tecnologies disponibles en l'actualitat per a la generació d'energia renovable en EDAR. Una altra quant a l'estat de la tecnologia per a la recuperació d'energia en xarxes d'aigua existents mitjançant maquinària hidràulica. Per a completar el marc de contextualització, la revisió es va ampliar realitzant una cerca exhaustiva de casos d'estudi reals d'aplicació d'aquesta tecnologia en EDAR. En aquesta fase es van identificar 49 casos d'estudi a nivell mundial, i es va analitzar el seu acompliment energètic.

(ii) Desenvolupament de la metodologia: Com a pas previ es van analitzar les metodologies existents per a avaluació del potencial d'aquesta tecnologia, dirigides a agents de governança. El resultat d'aquesta anàlisi es va comparar amb la informació obtinguda sobre casos d'estudi en la contextualització. Com a resultat, durant aquesta tesi s'ha desenvolupat una metodologia amb una nova perspectiva. En primer lloc, s'introdueix la necessitat de considerar el nivell al qual es produeix la presa de decisions, per a adaptar l'abast de l'estudi (grup de EDAR gestionades per un mateix agent). Una vegada identificat l'abast, la metodologia es desenvolupa en dues etapes. En l'etapa 1 (avaluació tècnica) el potencial de generació d'energia hidràulica s'estima de manera individual per a cada EDAR del grup analitzat. En l'etapa 2 (avaluació global) es proposa un mètode de decisió multicriteri introduint criteris de sostenibilitat, després de l'anàlisi del context en la zona d'estudi. L'alineació de la metodologia amb el seu context d'aplicació es considera una qüestió clau en aquesta proposta. En l'etapa 1, per a la identificació dels agents de governança responsables de la presa de decisions en les estratègies de descarbonització i definició de l'abast. En l'etapa 2, per a adaptar la metodologia i els criteris a les directrius existents i a les seues possibilitats reals d'aplicació.

(iii) Aplicació pràctica: Aquesta fase complementa l'estudi amb l'aplicació de les dues etapes esmentades a un cas pràctic. Així, es mostra l'aplicació de la metodologia a un grup de 186 EDAR de la Comunitat Valenciana (Espanya), que comparteixen la mateixa modalitat de finançament.

Els resultats obtinguts al llarg d'aquest treball de recerca han sigut publicats en 3 articles de revistes indexades (JCR).

Els resultats de la contextualització es van publicar en *l'Article I* i *l'Article II*. En *l'Article I* es va examinar el marc actual, i es van aplicar indicadors d'acompliment als casos reals, sobre la base del concepte d'autoproveïment amb energies renovables. Els resultats van il·lustrar la dificultat per a establir una norma general per a determinar la viabilitat d'aquesta tecnologia. En *l'Article II*, es van analitzar les dades de la maquinària hidràulica instal·lada, la generació d'energia i els factors de capacitat. Aquesta anàlisi va evidenciar la necessitat de continuar amb línies d'investigació per a millorar l'eficiència de la maquinària hidràulica en aquesta aplicació, ja que les fluctuacions de cabal típiques en les EDAR no permeten aprofitar actualment el potencial existent al màxim. Els resultats d'aquesta fase en general van demostrar que existeix una experiència real en l'aplicació pràctica d'aquesta tecnologia que no s'està utilitzant per al desenvolupament de tot el seu potencial en aquest sector.

La metodologia proposada es va presentar en *l'Article II* (etapa 1, avaluació tècnica) i en *l'Article III* (etapa 2, avaluació global). En *l'Article II* es va validar el mètode per a l'avaluació individual de potencial tècnic, a partir de l'anàlisi de metodologies existents i dels casos d'estudi identificats en la contextualització. Se suggereix la necessitat d'incloure en el procés de decisió altres consideracions, a més de la viabilitat econòmica, que és l'únic criteri en les metodologies prèvies. Així, es proposa que el límit per a determinar la viabilitat es base exclusivament en criteris tècnics conforme a l'estat de l'art de la tecnologia, en lloc d'econòmics. En *l'Article III* es va desenvolupar el mètode de decisió multicriteri, basat en les directrius de l'instrument de governança per a aigües residuals a Espanya (Plan Nacional de Depuración, Saneamiento, Eficiencia, Ahorro y Reutilización, conegut com a Plan DSEAR). Per a la selecció dels criteris en les tres dimensions de sostenibilitat (econòmica, mediambiental i social), es va elaborar un qüestionari amb criteris aplicables en aquest context, extrets després d'una revisió d'estudis d'aplicació de mètodes multicriteri en EDAR o energies renovables.

Finalment, en *l'Article III* es va aplicar la metodologia a un grup de 186 EDAR de la Comunitat Valenciana. En l'etapa 1 es van identificar 34 plantes amb potencial tècnic, estimant una generació d'electricitat de 340,472 kWh/any. Com a troballa d'aquesta fase es va observar la possibilitat d'augmentar aquest potencial fins a un 37.5%, en cas de ser viables modificacions dels punts d'abocament. En l'etapa 2, sobre la base del PDSEAR i els qüestionaris, es van definir 10 criteris, considerant les tres dimensions de sostenibilitat. Això va mostrar que, quan els resultats de l'etapa 1 es posen en el context de sostenibilitat en l'etapa 2, s'obté una nova perspectiva. Aquesta investigació demostra que, en el marc d'un desenvolupament sostenible, la recuperació d'energia hidràulica de l'aigua residual podria ser una opció més en la descarbonització d'aquest sector. Prenent com a base aquesta proposta, agents de governança per a la gestió d'aigües residuals en un altre context podrien desenvolupar metodologies similars adaptades al seu propi entorn.

Contents

Abbreviations

Acronyms

AV: Aggregate Value

BOD: Biological Oxygen Demand

CF: Carbon Footprint

CHP: Combined Heat and Power

COD: Chemical Oxygen Demand

CS: Case Study

DEM: Digital Elevation Model

ELECTRE: ELimination Et Choix Traduisant la REalite

EPSAR: Valencian Wastewater Treatment Agency

GHG: Greenhouse Gases

GIS: Geographic Information Systems

ID: Identification Number

KPI: Key Performance Indicators

LCA: Life Cycle Analysis

MCDA: Multi-Criteria Decision Analysis

MCDM: Multi-Criteria Decision Making

PAT: Pump As Turbine

PDSEAR: Plan for Wastewater Treatment, Sanitation, Efficiency, Savings and Reuse

PE: Population Equivalent

PROMETHEE: Preference Ranking Organization METHod for Enrichment Evaluations

PU: Pollution Units

RES: Renewable Energy Systems

SAW: Simple Additive Weighting

SDGs: Sustainable Development Goals

STP: Sewage Treatment Plant

TSS: Total Suspended Solids

UN: United Nations

WSM: Weighted Sum Method

WWTP: Wastewater Treatment Plant

Symbols

g: acceleration due to gravity (m/s^2)

H: available head (m)

n: number of criteria

P: power (W)

Q: volume flow rate (m^3/s)

w: weighting for each criterion i

x: score for scenario j

ρ: water density (kg/m^3)

η: overall efficiency

Chapter 1
Introduction

1.1. Motivation

The Agenda 2030 was adopted by the UN (United Nations) in 2015 to establish a plan of action towards sustainability, that considers the economic, environmental, and social dimensions. The 17 SDGs (Sustainable Development Goals) included in this plan can interact with each other, so they should not be regarded separately either (Ament et al., 2020; Coscieme et al., 2021; Hegre et al. 2020). Since the wastewater treatment industry is a large consumer of energy, it is necessary to apply the sustainability approach to wastewater systems to simultaneously achieve several of these goals, such as SDG 6 (Clean water and sanitation), SDG 7 (Affordable and clean energy), SDG 11 (Sustainable cities and communities), and SDG 13 (Climate actions) (Delanka-Pedige et al., 2021; UN-WWAP, 2017).

The energy demand for wastewater treatment currently accounts for a significant percentage of the total energy consumption in many countries worldwide. Some estimations point to data of about 0.8-1% for European countries, such as Italy, Switzerland, or Germany (Bousquet et al., 2017; Diaz-Elsayed et al., 2019; Ganora et al., 2019; Longo et al., 2016; Wang et al., 2016), 0.5% in South Korea (Chae et al., 2015), 0.25% in China (Chen et al., 2020), 0.6% in USA (Chen et al., 2020; Gu et al., 2017) or 0.4% in Australia (NSW Government, 2019). The energy demand at a particular WWTP (wastewater treatment plant), mainly as electricity, depends on several factors, such as the size and location, the pollutant load, and the required removal efficiency. All these factors are also considered in the selection of the treatment processes, and the energy requirements will ultimately depend on this choice too (Musabandesu & Loge, 2021; Wang et al., 2012). This consumption is one of the main costs during the operation of a WWTP. It is also a major source for the high levels of CF (carbon footprint) typically reported by these facilities, mainly due to the indirect emissions of GHGs (greenhouse gases) related to the use of electricity (Nakkasunchi et al., 2021).

In the next decade, the energy needs for this purpose will likely be intensified due to the expected population growth and the increasing requirements for sewage treatment to protect the aquatic environment. According to the UN World Water Development Report (UN-WWAP, 2017), the global demand for water in the world could increase a 50% by 2030, whilst about 80% of the wastewater generated around the world in 2017 was still discharged into the environment with no treatment at all. Additionally, as awareness of emerging pollutants also increases, standards for the quality of effluents become stricter, so further treatment processes will be required, also contributing to the future rise in this energy demand (Capodaglio & Olsson, 2020; Necibi et al., 2021; Yan et al., 2016; Zhang et al., 2015).

In this context, recent strategies in wastewater governance strive for the decarbonization of this industry, along with general energy policies (Chae et al., 2015; Maktabifard et al., 2018). For instance, in 2011, after planning a national roadmap for a reduction of total GHGs emissions, South Korea established specific goals for WWTPs, as in 2007 their share represented 3.5%. So their goals were set expecting to achieve 50% self-sufficiency by 2030 (Chae & Kang, 2013; R. Korea Ministry Environment, 2017). At lower geographical levels there are many other initiatives promoting the progressive installation of RES (renewable energy systems) (Qandil et al., 2021), such as those in Portugal (Waterworld, 2020) or Spain (Canal de Isabel II, 2020) aiming for a corporative energy neutrality by 2030, with 100% renewable energy production at their own facilities. Nowadays, this neutrality is feasible but still a challenge, as in general, there is not a standalone technology that can help a WWTP to become fully energy-self-sufficient (Chae & Kang, 2013; Maktabifard et al., 2018).

Decarbonization roadmaps aiming for sustainable wastewater systems must consider simultaneous actions, improving operational efficiencies to reduce energy consumption, and implementing technologies to generate RE (Maktabifard et al., 2018; Nakkasunchi et al., 2021). Due to this need for RE many research studies have explored different options in recent years. The options include external sources, such as solar energy or wind, and internal, when some form of energy is recovered from wastewater. Embedded energy that can be recovered includes chemical (from biogas, microbial fuel cells, microalgae systems), thermal, and mechanical energy (Capodaglio & Olsson, 2020; Del Río-Gamero et al., 2020; Diaz-Elsayed et al., 2019; Guerra-Rodríguez et al., 2020; Maktabifard et al., 2018). Most studies have focused on chemical energy, particularly CHP (combined heat and power) with biogas, since this form of energy usually presents the highest potential (Ali et al., 2020; Diaz-Elsayed et al., 2019; Nakkasunchi et al., 2021). However, biogas is generated in anaerobic processes, and due to their complexity, they can typically be found only in the largest plants (Gandiglio et al., 2017; Tchobanoglous, et al., 2014). A study in the USA estimated that 8.3% of the WWTPs could generate biogas (Scarlat et al., 2018), and another research in Europe identified 19.1% (Gandiglio et al., 2017). Particularly in Spain, according to the Ministry data, it would only be feasible at 5.6% of the plants (Ministry for Ecological Transition & Demographic Challenge, 2021). Many countries around the world present similar shares, with large numbers of small plants where CHP might not be an option (Gandiglio et al., 2017; García-López et al., 2021; UN-WWAP, 2017).

Therefore, alternative RE sources, either external or internal, need to be explored to provide a wider range of options for all kinds of plants (Chae et al., 2015). Bearing in mind the 2030 horizon, mature technologies able to be implemented in the short term, such as solar and wind energy, should be considered first (Del Río-Gamero et al., 2020; Gu et al., 2017; Guo et al., 2019; Maktabifard et al., 2018).

Hydropower is also a mature technology. However, the possibility of application to existing wastewater systems is less known (Adeyeye et al., 2021; Diaz-Elsayed et al., 2019; Kougias et al., 2019; Maktabifard et al., 2018). This lack of awareness has been reported. Kretschmer et al. carried out a survey in 2018 with four different groups of stakeholders (wastewater utilities, municipalities, energy suppliers, and housing cooperatives). The survey studied rate of awareness of several technologies (biogas, thermal, sludge incineration, and hydropower) for the first two groups. Hydropower had the lowest rate in both, 77% compared to 98% for biogas, and 14% compared to 48% respectively.

This technology can recover mechanical energy from wastewater. The potential power can be estimated with two basic parameters (available head, and flow rate) so the technical and economic feasibility can be assessed. Based on that, in the last decade hydropower has started to be studied as a possible solution for energy recovery in urban water systems (Bekker et al., 2021; Choulot et al., 2012; Gallagher et al., 2015a; McNabola et al., 2013;) and wastewater systems (Ak et al., 2017; Bousquet et al., 2017; García et al., 2021; Power et al., 2014). On the one hand, most of the published articles on hydropower potential assessment applied to WWTPs have conducted individual studies at a plant level, either theoretical or experimental (Ak et al., 2017; Berger et al., 2013; Chae & Kang, 2013; Chae et al., 2013, 2015; Che Munaaim et al., 2018; Guzmán-Avalos et al., 2023; Loots et al., 2015). On the other hand, studies addressed to stakeholders for global assessment have proposed and applied methodologies at a country level (Bekker et al., 2022; Bousquet et al., 2017; García et al., 2021;

Mitrovic et al., 2021; Power et al., 2014; Punys & Jureviˇcius, 2022). However, none of these methodologies has regarded that in wastewater governance there could be other decision-making stakeholders at an intermediate level, so their application at that level might not provide complete information. Besides, all the methodologies evaluated during this research focus on technical assessment and economic feasibility only, whereas nowadays, there is no doubt that the sustainability approach in decision-making processes is necessary to reach the SDGs (An et al., 2017; Starkl et al., 2022; Sueyoshi et al., 2022). Only the most recent study (Punys and Jureviˇcius; 2022) added environmental considerations but still did not consider the necessary social dimension (Adeyeye et al., 2021, 2022; Helgegren et al., 2021; Muhammad Anwar et al., 2021).

Finally, analyzing as well practical applications of RES for the wastewater sector, the lack of awareness about hydropower is also noticeable. Several projects have been conducted with the aim of improving wastewater systems sustainability by developing tools and guidelines for decision-making. Some of them, such as the European initiatives ENERWATER (ENERWATER, 2021; Longo et al., 2019; Mauricio-Iglesias et al., 2020), POWERSTEP (Maktabifard et al., 2018; POWERSTEP, 2021), or ECAM (Saidan et al., 2019; VaCCliM, 2021) are focused on energy and associated CF, whilst others, like SMART-Plant (Larriba et al., 2020; Maktabifard et al., 2018; SMART-Plant, 2021), IWAMA (IWAMA, 2021) or R3Water (Maktabifard et al., 2018; R3Water, 2021), have a broader approach and consider additional environmental impacts and resources recovery options. Similar projects have also been conducted by the World Bank for other regions, such as Latin America and the Caribbean (Rodríguez et al., 2020) or East Asia and Pacific (Vazquez Alvarez & Buchauer, 2014). Most of these tools consider biogas as the main option for RE generation. Generally, hydropower is not even included, or very little information endorses the technology, so it often appears as the least attractive option. An example of this is the local approach for Portugal and North Spain carried out within the project AQUALITRANS (AQUALITRANS, 2021).

Thus, the motivation for this research stems from the need to fully explore all options for RE generation, that could be implemented in the short term at WWTPs, as part of their decarbonization roadmaps. Previous studies for hydropower assessment have shown that, even though the potential might not be as high as for other technologies, some potential exists, and some energy could be recovered. However, the existing methodologies for hydropower potential assessment could be completed with a broader perspective, and the energy tools for wastewater systems completed with more information about the possibilities of hydropower. The methodologies addressed to wastewater stakeholders have not considered the sustainability perspective, which should include all three dimensions. The proposed methodology in this thesis integrates economic, environmental, and social factors, providing the broader approach needed for decision-making in a sustainability framework.

1.2. Aim and Objectives

The final aim of this thesis is to develop a methodology, specifically addressed to decision-making stakeholders in the wastewater industry, to assess hydropower potential for energy recovery.

The specific objectives to achieve this aim are the following:

1. To conduct a review of the state-of-the-art in two research lines. On the one hand, on the energy needs for wastewater treatment, from a global perspective, and current options to recover energy from wastewater. On the other hand, recent studies of hydropower technology at a small scale to recover energy from existing networks.

2. To determine factors influencing energy consumption as well as foreseen trends in energy demand for wastewater treatment worldwide. Simultaneously, to identify available options for renewable energy generation at WWTPs, applicable in the short term.

3. To identify real case studies of hydropower technology applied to wastewater systems worldwide and define suitable indicators to analyze their performance in order to identify the possibilities and current limitations of this technology.

4. To analyze the existing methodologies for hydropower potential assessment to evaluate their applicability in the current framework.

5. To propose a methodology based on the analysis of the existing background for hydropower potential assessment in wastewater systems, suitable to be tailored to any specific context.

6. To define appropriate economic, environmental, and social factors to develop the methodology within a sustainability framework.

7. To apply the proposed methodology to a case study to illustrate the methodological process and to contrast the results with the current situation in the analyzed region.

Considering the three stages of this research, objectives 1, 2, and 3 are related to the **contextualization stage**, whereas objectives 4, 5, and 6 correspond to the **development of the assessment methodology**, and objective 7 to its **practical application**.

1.3. Thesis Organization

This thesis document consists of 7 chapters, following the structure required by the Universitat Politècnica de València for a thesis by publication.

Chapter 1 presents the overall introduction of this research, providing the context, and describing the motivation, the main aim and objectives, and the structure of the document.

The following three chapters correspond to the three papers published in JCR indexed journals during this thesis, also according to the specific requirements from the Ph.D. Programme in Water and Environmental Engineering.

Chapter 2 corresponds to Publication I, "*Energy Self-Sufficiency Aiming for Sustainable Wastewater Systems: Are All Options Being Explored?*", where the general context is analyzed, identifying the research gap addressed throughout this research. The article presents the state of the art of renewable energy options currently applied to wastewater systems, with a particular focus on hydropower. Real case studies applying this technology were searched and evaluated considering energy self-sufficiency indicators. One of the main findings at this stage was the lack of awareness about hydropower as an option within the wastewater industry, which led to the need of exploring further the existing real case studies to complete the framework.

Chapter 3 corresponds to Publication II, "*Hydropower Technology for Sustainable Energy Generation in Wastewater Systems: Learning from the Experience*", where the current framework of hydropower application to wastewater systems is completed. This article includes an analysis of the technical performance of the identified real case studies, as well as of the existing methodologies for hydropower potential assessment. After a comparison of both, existing experience and existing assessment methods, the article presents the first step of the methodology developed during this research. Like all other previous assessment methodologies, this step only considers the technical dimension. However, the results from both, Publication I and II, highlighted the need to also introduce environmental and social factors in the decision-making process, which led to develop further the methodology for a sustainable approach.

Chapter 4 corresponds to Publication III, "*Exploring Options for Energy Recovery from Wastewater: Evaluation of Hydropower Potential in a Sustainability Framework*", which completes this research by providing a new approach to the existing knowledge in this field. This article presents the second step of the proposed methodology, a MCDA method for global assessment, which introduces factors in the decision-making process considering all three dimensions of sustainability (economic, environmental, and social). Finally, it applies the complete methodology to a case study, a group of 186 WWTPs in the region of Valencia, selected according to their management model.

Chapter 5 presents a general discussion of the results obtained throughout this research, simultaneously evaluating the fulfillment of the established objectives.

Chapter 6 summarizes the main conclusions of this thesis and provides some recommendations for further research.

Chapter 7 includes the list of references.

The publication data of the three articles included as chapters 2, 3, and 4 are the following:

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

Authors:	Rosa M. Llácer-Iglesias, P. Amparo López-Jiménez and Modesto Pérez-Sánchez
Journal:	Sustainability. ISSN: 2071-1050. JCR IF: 3.9 (2022); Q2 (Environmental Sciences; Environmental Studies)
Status:	Published in May 2021. Sustainability 2021, 13, 5537 https://doi.org/10.3390/su13105537

Publication II: *"Hydropower Technology for Sustainable Energy Generation in Wastewater Systems: Learning from the Experience"*

Authors:	Rosa M. Llácer-Iglesias, P. Amparo López-Jiménez and Modesto Pérez-Sánchez
Journal:	Water. ISSN: 2073-4441. JCR IF: 3.4 (2022); Q2 (Water Resources; Environmental Sciences)
Status:	Published in November 2021. Water 2021, 13(22), 3259 https://doi.org/10.3390/w13223259

Publication III: *"Exploring Options for Energy Recovery from Wastewater: Evaluation of Hydropower Potential in a Sustainability Framework"*

Authors:	Rosa M. Llácer-Iglesias, P. Amparo López-Jiménez and Modesto Pérez-Sánchez
Journal:	Sustainable Cities and Society. Print ISSN: 2210-6707; Online ISSN: 2210-6715. JCR IF: 11.7 (2022); Q1 (Construction & Buildings Technology; Energy & Fuels; Green & Sustainable Science & Technology)
Status:	Published in April 2023. Sustainable Cities and Society, Volume 95, August 2023, 104576 https://doi.org/10.1016/j.scs.2023.104576

1.4. Materials and Methods

Against this background, this research seeks to establish a suitable bridge between the tools available for academics and wastewater stakeholders to assess renewable energy options, and hydropower assessment methodologies addressed to governance stakeholders. Concerning the latter, this study also develops a methodology for hydropower potential assessment in wastewater systems, but with a novel approach, integrating the 3 dimensions of sustainability in the decision-making process. Besides, this proposal considers that, the integration of the methodology into the context, is a key issue for effective real application. Hence, all the stages of this research include a thorough analysis of the context, of the existing background and the previous experience, aiming for an alignment of the methodology with the management framework.

The three publications in the following chapters include a detailed description of the materials and methods used at each stage of the research process. They can be summarized as follows.

In the contextualization stage a literature review of the state of the art was carried out to achieve *objectives 1 and 2*. Then, to complete this contextualization according to *objective 3*, an exhaustive search of existing case studies of hydropower applications to WWTPs was conducted. The search process itself applied a broad approach, and some feedback was introduced during the different steps. Firstly, to identify as many real case studies as possible from publicly available data. So, after the first screening of the retrieved documents, the search was extended beyond the academic literature and the inclusion and exclusion criteria were revised. Secondly, for each WWTP identified as a real case study, the search was iterated seeking published data about their general energy profile and performance. In the following step, these data were further analyzed to obtain proper key performance indicators (KPI) to enable comparisons and the interpretation of results for the aim of this research.

The methodology developed and applied to a case study (Valencia Region) in the following stages of the research, consists of 2 steps:

- Step 1 (technical assessment) estimates the individual hydropower potential at each WWTP (*objectives 4 and 5*).
- Step 2 (global assessment) evaluates the group of potential sites applying a MCDA method with sustainability criteria (*objective 6*).

To obtain the input data in step 1 (technical assessment), the methodology uses publicly available data from institutional organisms and Geographic Information Systems (GIS) and Digital Elevation Models (DEM). So, from the UTM coordinates of the WWTP and the corresponding discharge point, the available gross head can be estimated. The average flow rate of the effluent at the outlet can be estimated from annual volume discharged displayed in basin organisms' reports.

For the application of step 1 to the case study in the Valencia Region (objective 7), detailed data for each WWTP were retrieved from EPSAR´s website. The data processed for this study were: location (UTM coordinates), municipalities served, size (volume and load), type of treatment (anaerobic processes or not), electricity consumption, renewable energy generation, and type of discharge (discharge into water bodies, ground or sea, or use of the reclaimed water for irrigation). The data for the corresponding discharge points were extracted from the annual reports available on the 2 basin agencies' websites, namely Júcar and Segura. The data processed were: location (coordinates), volume discharged, and receiving water body. A geovisualization tool specific from this region, available on the Valencian Cartographic Institute's website was used to estimate the head. All estimations were conservative and strict.

To introduce the sustainability approach in the decision-making process the methodology applies a MCDA method in step 2. MCDA methods usually consist of the following steps: (i) goal definition, (ii) criteria selection, (iii) criteria scores definition, (iv) weighting determination, (v) evaluation and aggregation.

As mentioned, the possibility of integration into existing management tools was also considered a key point for an effective application. Therefore, an analysis of the context was necessary in this step too. Bearing in mind that for *objective 7* the case study to illustrate the methodology would be selected within the Spanish context, the guidelines in the wastewater governance instrument in Spain (PDSEAR) determined most of the choices made during the development of the methodology.

(i) Goal definition: One of the main objectives of this study was to propose a translatable methodology that could be directly applied by stakeholders. Hence, the selected method should fulfill the following requirements: low complexity, flexibility to enable extrapolation to other case studies, no need for specialized skills or specific software, and flexibility to be modified under changes in circumstances. Another important issue is that the aim of this step, is to evaluate a number of plants as a group, not individually. According to all these requirements, the weighted sum method (WSM) or simple additive weighting (SAW) was selected as the basis to develop the methodology, tailored for the case study in this research.

(ii) Criteria selection: A new literature review with a focus on MCDA applied to WWTPs and/or RES was conducted. From that, a range of sustainability criteria were extracted, to select those suitable to be considered in the decision-making process, to install RE technologies at wastewater treatment plants (WWTPs). This information was aggregated in a questionnaire, to gather the opinion of the main stakeholders, adding some contributions from the authors according to the proposed approach and scope of this study. This questionnaire tried to be exhaustive, so it could be used to develop similar methods in other contexts. In the practical application a set of criteria that could be suitable for a CS in the Spanish context was selected, provided the necessary data were available from institutional websites. To gather additional information, the questionnaire was sent to 2 main stakeholders, and the answers were used to validate the consistency of the proposal.

(iii) Criteria scores definition: The criteria scores were defined according to the PDSEAR guidelines and the available data for the Valencia Region.

(iv) Weighting determination: The weighting determination was based on the literature review, the PDSEAR guidelines, and the questionnaires.

(v) Evaluation and aggregation: The final evaluation expression and priority ranking was also aligned to the PDSEAR guidelines.

Chapter 2
Publication I

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

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

Journal: Sustainability (ISSN: 2071-1050)

JCR IF: 3.9 (2022); Q2 (Environmental Sciences; Environmental Studies)

Status: Published in May 2021. Sustainability 2021, 13, 5537

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Abstract

In upcoming years, water demand is expected to soar 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.

2.1. 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 (Ament et al., 2020; Coscieme et al., 2021; Hegre et al. 2020). 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 (Delanka-Pedige et al., 2021; UN-WWAP, 2017).

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 (Musabandesu & Loge, 2021; Wang et al., 2012).

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 (Avilés et al., 2019; Capodaglio & Olsson, 2020; Guerrini et al., 2016, 2017; Longo et al., 2016). 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 (Guerrini et al., 2017; Longo et al., 2016). 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 (Avilés et al., 2019; Guerrini et al., 2017; Revollar et al., 2020). 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 (Guerrini et al., 2017; Hanna et al., 2018; Longo et al., 2016).

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 (Capodaglio & Olsson, 2020; Guerrini et al., 2017; Revollar et al., 2020; Wakeel et al., 2016). However, this contribution is not always considered (Capodaglio & Olsson, 2020). 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 (Avilés et al., 2019; Guerrini et al., 2016; Hanna et al., 2018). 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 (Capodaglio & Olsson, 2020; Guerrini et al., 2016, 2017; Hanna et al., 2018; Longo et al., 2016; Wakeel et al., 2016). 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 (Avilés et al., 2019; Guerrini et al., 2017; Revollar et al., 2020). 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 (Avilés et al., 2019; Guerrini et al., 2017; Hanna et al., 2018).

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 (Capodaglio & Olsson, 2020; Gu et al., 2017; Guo et al., 2019; Maktabifard et al., 2018; Musabandesu & Loge, 2021; Wakeel et al., 2016). 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 (Bousquet et al., 2017; Diaz-Elsayed et al., 2019; Ganora et al., 2019; Longo et al., 2016; Wang et al., 2016), 0.5% in Korea (Chae et al., 2015), 0.25% in China (Chen et al., 2020), or 0.6% in USA (Chen et al., 2020; Gu et al., 2017).

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 (Nakkasunchi et al., 2021).

On the one hand, new policies worldwide strive for the decarbonization of energy production systems in general (Chae et al., 2015; Maktabifard et al., 2018). 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 (Chae & Kang, 2013). At lower geographical levels, many other initiatives promoting the progressive installation of renewable energies at water systems can be found (Qandil et al., 2021).

On the other hand, in the next years, energy needs for wastewater treatment are expected to soar. According to the UN World Water Development Report from 2017 (UN-WWAP, 2017), 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 (Zhang et al., 2015), 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 (Smith et al., 2018). Therefore, in upcoming years, the installation of new facilities will be needed, whereas some retrofitting of existing plants will be necessary too (Velasquez-Orta et al., 2018). 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 (Capodaglio & Olsson, 2020; McCarty et al., 2011). Similarly, awareness of contaminants of emerging concern (Diaz-Elsayed et al., 2019; Necibi et al., 2021) 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 (Yan et al., 2016; Zhang et al., 2015). With that, both, associated economic costs and environmental impacts will rise too.

2.1.1. 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 (Nakkasunchi et al., 2021).

- 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 (Avilés et al., 2019; Longo et al., 2018; Nakkasunchi et al., 2021). Additionally, by implementing processes with lower energy demand, like those based on anaerobic processes for secondary treatment (Musabandesu & Loge, 2021; Budych-Gorzna et al., 2021).
- Second, by the implementation of renewable energy generation technologies (Diaz-Elsayed et al., 2019; Gandiglio et al., 2017; Maktabifard et al., 2018), 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 (Ali et al., 2020; Chae & Kang, 2013; Gu et al., 2017; Hao et al., 2015; Longo et al., 2019; McCarty et al., 2011).

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 (Chae & Kang, 2013; Maktabifard et al., 2018). Further, the expected increase of demand for energy in the near future will make that goal even more difficult to achieve (Gandiglio et al., 2017; Yan et al., 2016). Thus, further research is needed in both parallel lines, improving the energy efficiency of the process and facilities, and renewable energy generation on site (Nakkasunchi et al., 2021).

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 (Capodaglio & Olsson, 2020; Del Río-Gamero et al., 2020; Diaz-Elsayed et al., 2019; Guerra-Rodríguez et al., 2020; Maktabifard et al., 2018).

- 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 (Ali et al., 2020; Gandiglio et al., 2017; Lu et al., 2015; Maktabifard et al., 2018; McCarty et al., 2011).
- 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 (Neugebauer et al., 2015; Schestak et al., 2020; Spriet et al., 2020).
- Mechanical recovery of energy, like hydropower, however, has received less attention (Diaz-Elsayed et al., 2019; Maktabifard et al., 2018). 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 (Bekker et al., 2021; Choulot et al., 2012; Gallagher et al., 2015a; McNabola et al., 2013; Mitrovic et al., 2021; Pérez-Sánchez et al., 2017) and wastewater systems in particular (Ak et al., 2017; Bousquet et al., 2017; Che Munaaim et al., 2018; García et al., 2021; Power et al., 2014).

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 (Ali et al., 2020; Diaz-Elsayed et al., 2019; Nakkasunchi et al., 2021). For example, in the UK, it was estimated that biogas represents about 90% of the energy generated from renewable sources in the water sector (Power et al., 2014). However, usually only larger plants include anaerobic processes for wastewater treatment, or more commonly, for sludge digestion. According to Gandiglio et al. (2017), 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 (Del Río-Gamero et al., 2020; Gu et al., 2017; Guo et al., 2019; Maktabifard et al., 2018).

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

2.1.2. 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 (Diaz-Elsayed et al., 2019; Maktabifard et al., 2018).

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 (Longo et al., 2019; Maktabifard et al., 2018; Mauricio-Iglesias et al., 2020), POWERSTEP (Loderer et al., 2017; Maktabifard et al., 2018), or ECAM (Saidan et al., 2019) are specifically focused on energy and associated GHG emissions. Whereas others, like SMART-Plant (Larriba et al., 2020; Maktabifard et al., 2018) or R3Water (Maktabifard et al., 2018), 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 (Rodríguez et al., 2020) or East Asia and Pacific (Vazquez Alvarez & Buchauer, 2014). 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 (Maktabifard et al., 2018). 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 (Zhang et al., 2015). 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 (Diaz-Elsayed et al., 2020; Kretschmer et al., 2018). 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 (Neto et al., 2018), 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.

2.2. 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.

2.2.1. 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. (2012) 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 2.3.

2.2.2. 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 2.1, the energy issue at wastewater systems needs to be tackled in two parallel lines, improving energy efficiency and renewable energy technologies implementation (Nakkasunchi et al., 2021).

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 (Longo et al., 2016; Maktabifard et al., 2018; Palma-Heredia et al., 2020). 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 BOD5 of 60 g of oxygen per day (Longo et al., 2016). 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 $COD_{removed}$ (Longo et al., 2016; Maktabifard et al., 2018; Palma-Heredia et al., 2020), nutrients removal, such as kWh/kg $N_{eliminated}$ (Longo et al., 2016; Palma-Heredia et al., 2020) or suspended solids as kWh/kg $TSS_{removed}$ (Longo et al., 2016; Maktabifard et al., 2018; Palma-Heredia et al., 2020). Nevertheless, some authors like Longo et al. (2016) 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 (Longo et al., 2019).

All these KPIs might show a wide range of different values, depending on the effecting factors described in Section 2.1, such as the size of the plant or type of treatment (Guerrini et al., 2017; Hanna et al., 2018; Longo et al., 2016) 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 (Villazón et al., 2020). 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 (Sánchez-Ortiz et al., 2020).

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 2.1.

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 $kWh_{generated/year}$ (Longo et al., 2016; Palma-Heredia et al., 2020). Electric and thermal energy are usually considered separately, and for the purpose of this study, only electricity is considered.

Table 2.1. *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	Longo et al., 2016; Maktabifard et al., 2018; Palma-Heredia et al., 2020
Pollution Load		
Electricity consumed/ Population equivalent	kWh/PE-year	Longo et al., 2016
Electricity consumed/ Biodegradable organic matter removed	kWh/kg BOD	Longo et al., 2016; Maktabifard et al., 2018; Palma-Heredia et al., 2020
Electricity consumed/ Total organic matter removed	kWh/kg COD	Longo et al., 2016; Maktabifard et al., 2018; Palma-Heredia et al., 2020
Electricity consumed/ Nutrients removed	kWh/kg N [1]	Longo et al., 2016; Palma-Heredia et al., 2020
Electricity consumed/ Total suspended solids removed	kWh/kg TSS	Longo et al., 2016; Maktabifard et al., 2018; Palma-Heredia et al., 2020
Electricity consumed/ Global pollution removed	kWh/kg PU	Longo et al., 2016
Renewable Energy Generation		
(Total electricity production from renewable sources / Electricity consumed) x100 [2]	%	Chae & Kang , 2013; Hao et al., 2015 Longo et al., 2019 Palma-Heredia et al., 2020
(Electricity production from hydropower / Electricity consumed) x100 [3]	%	Chae & Kang , 2013;

[1] Nutrients usually include Nitrogen or Phosphorus separately.

[2] Energy self-sufficiency (%): Ratio (annual electricity generated with renewable technologies/annual WWTP consumption) x100.

[3] Hydropower contribution (%) to energy self-sufficiency.

When merging both basic data (electricity consumed and electricity generated per unit time), another KPI can be defined, electric energy self-sufficiency (Chae & Kang, 2013; Hao et al., 2015; Longo et al., 2019; Palma-Heredia et al., 2020). The ratio (total renewable electric energy production/total electric energy consumption) x 100%, also called energy independence (Chae & Kang, 2013) or carbon neutral efficiency (Gandiglio et al., 2017; Gu et al., 2017; Hao et al., 2015), was introduced in recent years, as an indicator directly related to the sustainability of a WWTP (Zhang et al., 2015).

In Palma-Heredia et al. (2020), 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 (Chae & Kang, 2013) 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 (Chae & Kang, 2013; Chae et al., 2015) 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 (Zhang et al., 2015), 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.

2.3. KPIs Applied to Real Case Studies

2.3.1. 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 2.1, there are clearly 2 leading countries in the number of sites applying this technology, Switzerland and Korea, with 10 and 11 case studies, respectively.

Table 2.2 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.

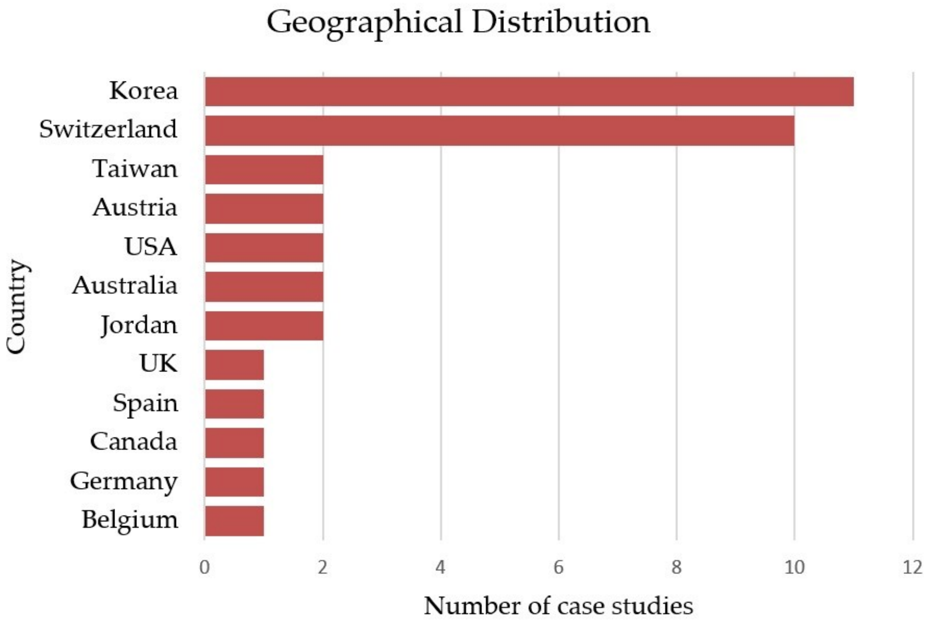

Figure 2.1. *Geographical distribution, number of hydropower case studies found per country/district.*

The first thing to notice, as shown in Figure 2.1 and Table 2.2, 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 (Bousquet et al., 2017; Diaz-Elsayed et al., 2019; Power et al., 2014). A total of 36 cases were identified, whereas the research carried out in 2017 by Bousquet et al. (Bousquet et al., 2017) included only 17 of these plants to develop their methodology. In Power et al. (2014), 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 (Diaz-Elsayed et al., 2019; Maktabifard et al., 2018).

Table 2.2. *Real case 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**	**Ren. Energy Technologies [4]**	**% Self-suff.[4]**	**Source**
Austria	Plobb -Seefeld [1]	Seefeld Zirl	2005	H	>100%	Choulot et al 2012
	Ebswien	Vienna (Simmering)	2009, 2013 [2]	H + S + W [5]	11% [7]	
Switzerland	Chaux-de- Fonds [1]	La Chaux-de-Fonds	2007, 2016 [2]	H + BCHP	65%	Rueetschi 2008
	Le Châble Profray	Val de Bagnes, station Verbier (Valais)	1993, 2008 [2]	N/A	N/A	Bousquet et al 2017
	La Douve 1	Aigle, Leysin (Vaud)	1989, 2000 [2]	N/A	N/A	
	La Douve 2	Aigle, Leysin (Vaud)	2001	N/A	N/A	
	L'Asse[1]	Nyon (Vaud)	1990	H + BCHP + S	66.1% [7]	
	Grächen	Grächen (Valais)	2011	N/A	N/A	
	Engelberg	Engelberg	2010	H + BCHP [6] + S	>100% [7]	
	Morgental (Hofen) [1]	Steinach (St. Gallen)	1916, 2014 [2]	H + BCHP [6] + S + W + T	>100% [7]	
	Aïre	Genève	before 2015 [3]	H + BH	N/A	
	La Louve [1]	Lausanne	2006	N/A	N/A	Power et al 2014
Germany	Emmerich (TWE)	Emmerich am Rhein	2000	H + BCHP	N/A	Bousquet et al 2017
UK	Esholt	Bradford (Yorkshire)	2009	H + BCHP	>100%	Bousquet et al 2017 Power et al 2014

Table 2.2. (Cont.)

Country/ District	Name of WWTP	Location	Year	Ren. Energy Technologies [4]	% Self-suff.[4]	Source
Spain	Sur	Getafe (Madrid)	before 2014 [3]	H + BCHP	91.2%	Lizarralde et al 2019
Belgium	Brussels-North	Brussels	before 2019 [3]	H + BCHP + S + T	30%	van Nuijs et al 2011
Australia	North Head	Sydney	2010	H + BCHP	58%	Bousquet et al 2017; Power et al 2014; Radcliffe 2018
	Gippsland Water Factory [1]	Maryvale (Gippsland Victoria)	2010	H + BCHP	40%	Daigger et al 2013
Jordan	As samra	Amman City	2008	H + BCHP	80%	Bousquet et al 2017; Choulot et al 2012
	As samra II	Amman City	2015	N/A	N/A	Bousquet et al 2017
Korea	Asan	Chungnam asan	2000	N/A	N/A	Chae et al 2013; Nah & Lee 2010
	Cheonan	Chungnam cheonan	2002	N/A	N/A	
	Jinhae	Gyeongnam jinhae	2004	N/A	N/A	
	Shinshun	Daegu	2005	N/A	N/A	
	Seoksu	Gyeonggi Anyang	2007	N/A	N/A	Nah & Lee 2010;
	Seobu	Daegu	2010	H + S	N/A	Chae et al 2013
	Chungju	Chungju	2011	N/A	N/A	Chae et al 2013
	Nan Ji	Seoul	2014	H + BCHP + S + T	51.6% [8]	Lee et al 2015
	Tan Chun	Seoul	before 2017 [3]	H + S + T	51.6% [8]	Choing 2019
	Joong Rang	Seoul	2015	H + BCHP + S	51.6% [8]	
	Seo Nam	Seoul	2015	H + BCHP + S + T	51.6% [8]	

Table 2.2. (Cont.)

Country/ District	Name of WWTP	Location	Year	Ren. Energy Technologies [4]	% Self-suff.[4]	Source
Taiwan	N/A	Taichung	before 2008 [3]	N/A	N/A	Bousquet et al 2017
	Hsinchu	Hsinchu	before 2008 [3]	N/A	N/A	
USA	Deer Island	Boston (Massachusetts)	2001	H + BCHP + S + W	26%	Bousquet et al 2017; Choulot et al 2012; Power et al 2014
	Point Loma	San Diego	2001	H + BCHP	>100%	Bousquet et al 2017; Power et al 2014
Canada	Clarkson	Mississauga	2015	H + BCHP	30.8% [7]	Regional Municipality Peel 2019

[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) x 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 (Bousquet et al., 2017; Choulot et al., 2012) and strong policies aiming for decarbonization of the energy system, especially remarkable for the WWT sector in Korea (Chae & Kang, 2013). However, whereas Switzerland is usually regarded in the literature as the pioneer country for this application (Bousquet et al., 2017; Choulot et al., 2012), 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 (Bousquet et al., 2017; Chae et al., 2015; Choulot et al., 2012; Diaz-Elsayed et al., 2019; Loots et al., 2015; Mitrovic et al., 2021; Power et al., 2014). Regarding this, it is important to remark that the sites shown in Table 2.2, 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 (Strazzabosco et al., 2020). 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 (Bousquet et al., 2017; Choulot et al., 2012; Loots et al., 2015; Power et al., 2014). Similar limitations within the wastewater sector were already reported by Strazzabosco et al. (2020).

Looking back at Table 2.2, out of Switzerland, where usually the topology provided high available head, it can be observed that many cases are located in big cities (Bousquet et al., 2017; Choing, 2019; Choulot et al., 2012; Power et al., 2014; van Nuijs et al. 2011). 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 (Bousquet et al., 2017; Power et al., 2014). However, even though energy benchmarking studies have proven that the economy of scale is generally applicable, provided the process, and other circumstances are similar (Capodaglio & Olsson, 2020; Gandiglio et al., 2017; Gu et al., 2017), 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 (Bousquet et al., 2017; Choulot et al., 2012; Power et al., 2014; Rueetschi, 2008). Another possible reason could be related to the availability of specialized management resources in larger plants, as usually happens in industrial organizations (Kaselofsky et al., 2021; Södergren & Palm, 2021; Tsvetkova et al., 2020; Villazón et al., 2020). 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 (Diaz-Elsayed et al., 2020; Kretschmer et al., 2018).

Apart from the real case applications summarized in Table 2.2, 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 (Chae & Kang, 2013; Chae et al., 2013, 2015), and more recently, Zeekoegat WWTP in South Africa (Loots et al., 2015) or Stonecutters Island STW in Hong Kong (DSD, 2019; Zhuang et al., 2020). 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) (Berger et al., 2013).

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 (Bousquet et al., 2017) or just Profay (Power et al., 2014), in others as Bagnes (Diaz-Elsayed et al., 2019) and even as Verbier. Thus, for a clearer identification, the name and location data in Table 2.2 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 (Choulot et al., 2012; Power et al., 2014). 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 (Bousquet et al., 2017).

The cases of La Louve or Gippsland are remarkable too (Daigger et al., 2013; Power et al., 2014). 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 (Daigger et al., 2013).

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 2.2. 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 2.2, 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 2.2), 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 2.2, also plotted in Figure 2.2, 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 2.2. 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 2.2 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.

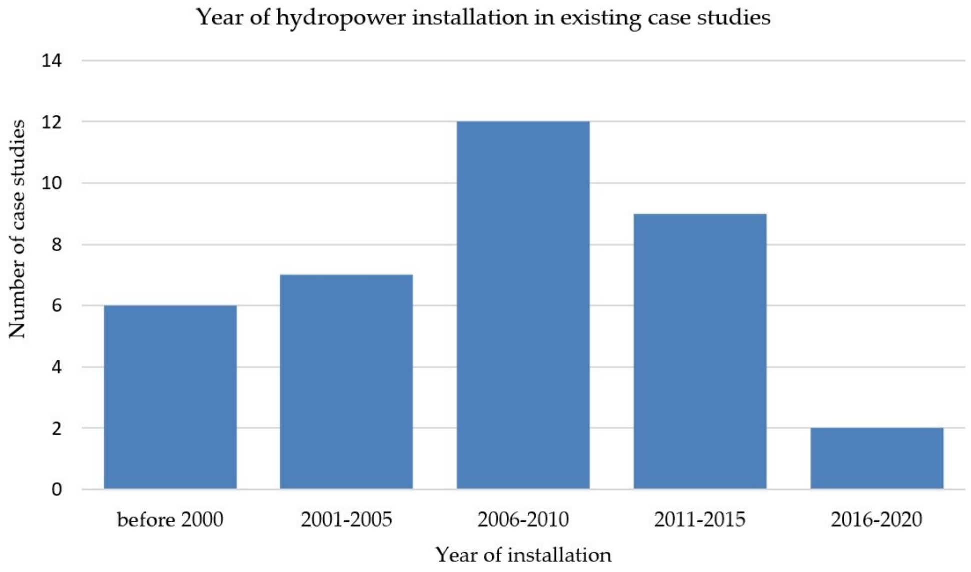

Figure 2.2. *Distribution of the number of hydropower case studies per year of installation (grouped in a five-year period).*

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.

2.3.2. 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 onsite for energy generation (both, electric, and thermal). Besides, for half of the plants (19), the total energy self-sufficiency KPI as defined in Section 2.2.2. 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 2.2.

From the energy data shown in Table 2.2., 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 2.2, 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 2.3.

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 2.3. 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 2.3.

Table 2.3. *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]	>100%	>100%
	Ebswien	11.0%	2.6%
Switzerland	L'Asse[1]	66.1% [3]	33.9% [4]
	Engelberg	>100% [3]	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) x100%.

[4] Value calculated applying KPI definition (annual electricity generated with hydropower/annual consumption) x100%.

[5] Values used for calculations correspond to different years.

Concerning the specific hydropower contribution to energy self-sufficiency, the limitation of available data was even stronger (Bousquet et al., 2017; Strazzabosco et al., 2020). Nevertheless, some important conclusions can also be drawn from the obtained results.

Firstly, in Table 2.3 and Figure 2.3, 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 (Bousquet et al., 2017; Choulot et al., 2012; Lizarralde et al., 2019; Power et al., 2014; Regional Municipality Peel, 2019; van Nuijs et al. 2011). 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%) (Bousquet et al., 2017), or only with a small contribution like in Clarkson (about 1%) (Regional Municipality Peel, 2019), 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 (Palma-Heredia et al., 2020; Sánchez-Ortiz et al., 2020; Villazón et al., 2020).

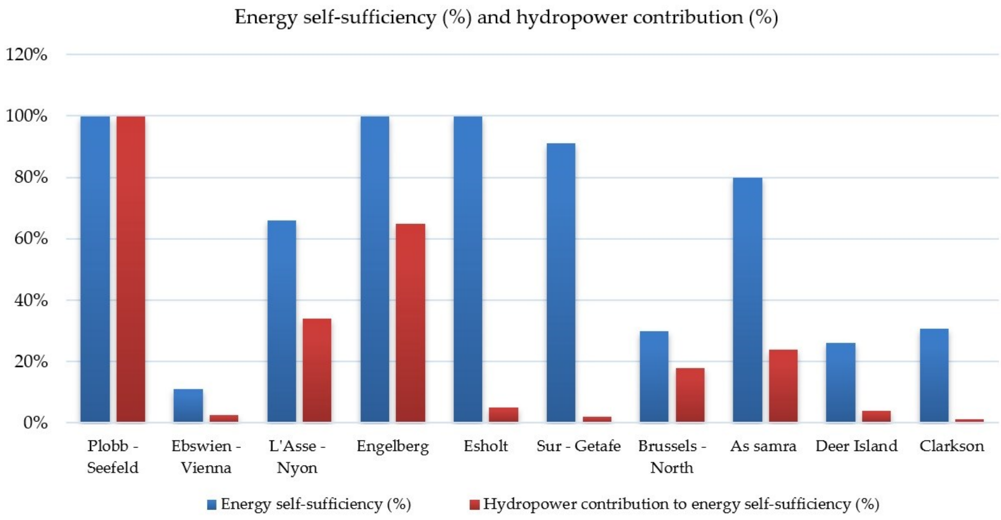

Figure 2.3. *Energy KPI values obtained for case studies analyzed: % Total self-sufficiency (blue bar) considering all renewable energy technologies applied and % individual contribution of hydropower to self-sufficiency (red bar).*

Secondly, in the cases where there is exchange beyond the boundary limits, the significance of the KPIs varies (Bousquet et al., 2017; Choulot et al., 2012; Daigger et al., 2013; Power et al., 2014). 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. (Berger et al., 2013). Other examples of the possible contribution of hydropower to plant self-sufficiency were estimated for Juru Regional STP in Malaysia with 0.7% (Che Munaaim et al., 2018) or Tatlar WWTP in Turkey with up to 34% potential (Ak et al., 2017).

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 (Södergren & Palm, 2021; Tsvetkova et al., 2020). However, the limitations of budget can often hinder their investments with higher restrictions than in the private sector, especially for smaller plants (Kaselofsky et al., 2021; Revollar et al., 2020; Södergren & Palm, 2021). 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 (Bergmann et al., 2017), 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 (Diaz-Elsayed et al., 2020; Ling et al., 2021; Södergren & Palm, 2021). 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 (Diaz-Elsayed et al., 2020; Ling et al., 2021; Longo et al., 2016). 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 (Bousquet et al., 2017; Diaz-Elsayed et al., 2019; Power et al., 2014).

Wastewater treatment needs and increasing water quality demands are global issues. Nowadays water policies in most countries trend to centralized systems (Diaz-Elsayed et al., 2019) but more recently some studies have pointed the convenience of shifting back to decentralized designs (Capodaglio & Olsson, 2020; Hafeez et al., 2021; Johannsen et al., 2021; Risch et al., 2021; Roefs et al., 2017). 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 (Loots et al., 2015; Power et al., 2014). If trends point to decentralized systems, these imply smaller plants, with their inherent characteristics and limitations to implement renewable energy technologies. The main appeal of hydropower is its flexibility, accessibility, and worldwide application (Chae & Kang, 2013; Loots et al., 2015; Mitrovic et al., 2021; Power et al., 2014; Radcliffe, 2018), without interfering in the treatment process itself and without the strict limitation of scale that other technologies do present (Ali et al., 2020; Di Capua et al., 2020; Hanna et al., 2018; Nakkasunchi et al., 2021; Riley et al., 2020).

2.4. 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 2.2, 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 2.2, 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 2.3 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.

Author Contributions

Conceptualization, R.M.L.-I., P.A.L.-J.,M.P.-S.; methodology, R.M.L.-I., P.A.L.-J.,M.P.-S.; writing—original draft preparation, R.M.L.-I.; writing—review and editing, P.A.L.-J., M.P.-S. All authors have read and agreed to the published version of the manuscript.

Chapter 3
Publication II

“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.

3.1. 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 (Delanka-Pedige et al., 2021; Elavarasan et al., 2021). One of them is SDG 6 ‘Clean water and sanitation’, which includes targets that are also critical for achieving other SDGs (Delanka-Pedige et al., 2021; Mercedes-García et al., 2021). At the same time, some SDGs demand actions to preserve natural resources, provide affordable and clean energy and tackle climate change (Elavarasan et al., 2021). 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 (Elavarasan et al., 2021).

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 (UN-WWAP, 2017). Water should not be regarded just as a consumer product, but as a valuable resource that must be protected, a social responsibility (EurEau, 2020). As such, opportunities to improve wastewater management should not be neglected (Kehrein et al., 2020a; UN-WWAP, 2017)

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 (Guerrini et al., 2016; García-López et al., 2021). 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 (UN-WWAP, 2017). This implies obtaining a high-quality effluent as a first goal, whilst simultaneously optimizing the use of other resources (Capodaglio & Olsson, 2020; Kehrein et al., 2020b). Since the electricity demand in wastewater treatment is usually very high (Capodaglio & Olsson, 2020; Revollar et al., 2021), actions are needed to deal with this environmental aspect including both efficiency improvement and renewable energy generation (Revollar et al., 2021; Zohrabian & Sanders, 2021). Figure 3.1 summarizes the global water cycle with main energy flows.

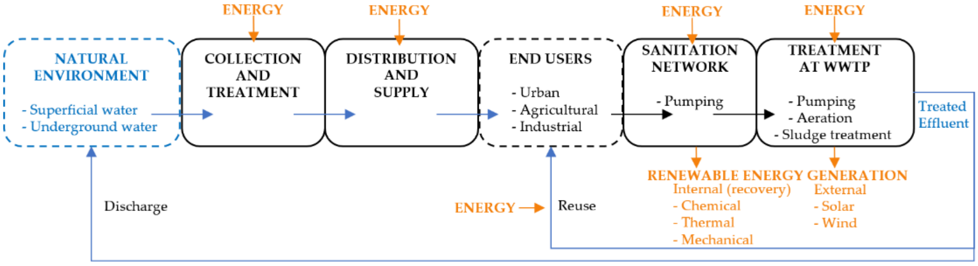

Figure 3.1. *Water cycle diagram*

Concerning renewable energies, generation from biogas is usually the main option considered for WWTPs (Diaz-Elsayed et al., 2019; Maktabifard et al., 2018; Nakkasunchi et al., 2021). Biogas production certainly is a very profitable technology for this industry (Campana et al., 2021; Rodríguez et al., 2020; Vazquez Alvarez & Buchauer, 2014) and ongoing research is continuously improving its performance and possibilities (Baena-Moreno et al., 2021; Ghimire et al., 2021; Wang & Nakakubo, 2021). Nevertheless, the still high complexity of the anaerobic processes required to generate biogas usually limits their application only to the largest plants (Gandiglio et al., 2017; Tchobanoglous, et al., 2014). For example, in Scarlat et al. (2018) 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 (Merlin et al., 2021) 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 (Gandiglio et al., 2017; García-López et al., 2021; UN-WWAP, 2017).

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/m^3 wastewater treated) (Capodaglio & Olsson, 2020; Gandiglio et al., 2017). Hence, their share in energy consumption is often larger than in volume of wastewater (García-López et al., 2021).

Therefore, the number of small WWTPs with these conditions is huge worldwide and expected to rapidly increase in upcoming years (Yan et al., 2017). Simultaneous increasing demand of water and higher protection of the aquatic environment will require new installations too (UN-WWAP, 2017). 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 (Merlin et al., 2021; UN-WWAP, 2017). Possible trends to decentralized sanitation systems would also increase the proportion of smaller plants (Reifsnyder et al., 2021; Risch et al., 2021; Zahediasl et al., 2021). Thus, other renewable energy options should also be explored to provide simpler alternatives for small plants (Chae et al., 2015). Even, as observed in recent studies, they could be applied as complementary systems for the largest ones (Del Río-Gamero et al., 2020; Jorge et al., 2021).

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 (Chae et al., 2015 ; Reifsnyder et al., 2021; Risch et al., 2021; Zahediasl et al., 2021).

3.1.1. 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 (EurEau, 2020; Rodríguez-Villanueva & Sauri, 2021; Södergren & Palm, 2021). Global policies and incentives are usually promoted by national governments with competences for management of water services (EurEau, 2020). Like the pioneer plan in Korea proposed a decade ago, specifically aimed at a reduction of GHGs emissions in WWTPs (Chae & Kang, 2013; R. Korea Ministry Environment, 2017) or the recently proposed global plan for improving efficiency in the wastewater sector in Spain (Ministry for Ecological Transition & Demographic Challenge, 2021). 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 (EurEau, 2020). Examples of this can be found in a number of countries, like the study for WWTPs in Madrid region in Spain (Ferrer-Polo et al., 2016), for Canton de Vaud in Switzerland (Canton de Vaud, 2018) or for Oregon in USA (ACWA, 2008).

There is a wide range of water management models in different countries and even in different regions within a country (EurEau, 2020), with regional organisms, basin agencies and municipalities frequently playing important roles as well, the latter often grouped in multi-municipal entities (Södergren & Palm, 2021; UN-WWAP, 2017). 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 (EurEau, 2020; UN-WWAP, 2017). 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 (Najar & Persson, 2021; Prochaska & Zouboulis, 2020). 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 (Waterworld, 2020) or Spain (Canal de Isabel II, 2020).

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.

3.1.2. 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 (Llácer-Iglesias et al., 2021a). However, as observed by some researchers (Adeyeye et al., 2021; Kougias et al., 2019; Kretschmer et al., 2018) 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 (Choulot et al., 2012; McNabola et al., 2014; Pérez-Sánchez et al., 2017), including WWTPs (Ak et al., 2017; Bekker et al., 2021). 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 (Ramos et al., 2000): (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 (Quaranta & Revelli, 2018; YoosefDoost & Lubitz, 2020; Zhou & Deng, 2017).

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 (BHA, 2012; Bracken et al., 2014; Williamson et al., 2014).

Previously published academic research on hydropower application to wastewater systems, either developed and applied methodologies for global potential assessment at a country (Bousquet et al., 2017; Power et al., 2014), or multi-country level (Mitrovic et al., 2021), or conducted individual feasibility studies at a plant level, experimental as in (Loots et al., 2015) or theoretical as in (Ak et al., 2017). 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 (García et al., 2021; Mitrovic et al., 2021). Environmental assessment in this application has already been studied (Gallagher et al., 2015b, 2015c; Ueda et al., 2019). 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 (Bracken et al., 2014; Kehrein et al., 2020a; Nautiyal & Goel, 2020). In their recent work Adeyeye et al. (2021) presented social viability aspects of hydropower application in urban water systems and Llácer-Iglesias et al. (2021a) also proposed a complementary approach related to energy self-sufficiency, identifying other driving factors for hydropower implementation at WWTPs.

3.1.3. Aim of This Study

As seen in Section 3.1.1, 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 (Najar & Persson, 2021; Palma-Heredia et al., 2020). Therefore, adjustment of the assessment methodologies mentioned in Section 3.1.2, at the same level as decision-making stakeholders, could provide them with more complete technical information about their renewable energy options (Södergren & Palm, 2021). With that, a forward step to real application of renewable energy technologies, as current global targets to tackle climate change require (Elavarasan et al., 2021; EurEau, 2020).

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:
    - Previous methodologies for potential assessment proposed in academic papers (described in Section 3.2.1);
    - Characteristics and performance of real case studies (methods described in Section 3.2.2 and results displayed in Sections 3.3.1 and 3.3.2).
2) To compare both—methodologies with data of the real case studies (methods described in Section 3.2.3 and results analyzed in Sections 3.3.1 and 3.3.2). 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 3.3.4. 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 3.3.3 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.

3.2. 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 3.2.1). In a second phase (Section 3.2.2), 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 3.2.3.

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 3.2 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) (Choulot et al., 2010, 2012; Loots et al., 2015). The potential power output is determined by the following general expression:

$$P = \rho \cdot g \cdot Q \cdot H \cdot \eta \qquad (3.1)$$

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:

$$\text{Capacity factor } (\%) = \frac{\text{Energy generated}}{\text{Installed power } 8760} \qquad (3.2)$$

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 (BHA, 2012; Nautiyal & Goel, 2020).

The selection of suitable machinery is very important (Choulot et al., 2012; Power et al., 2017). 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) (Choulot et al., 2012; Pérez-Sánchez et al., 2017). Archimedes screws and gravity water wheels are the most frequent examples of hydraulic machinery in open channels (Quaranta & Revelli, 2018; YoosefDoost & Lubitz, 2020). Conventional turbines can be classified into reaction (Francis, Kaplan, Deriaz, Propeller) and action or impulse turbines (Pelton, Crossflow, Turgo) (Jawahar & Michael, 2017; Pérez-Sánchez et al., 2017; Zhou & Deng, 2017). 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 (Kougias et al., 2019; Pérez-Sánchez et al., 2017). 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 (Delgado et al., 2019; Williamson et al., 2014).

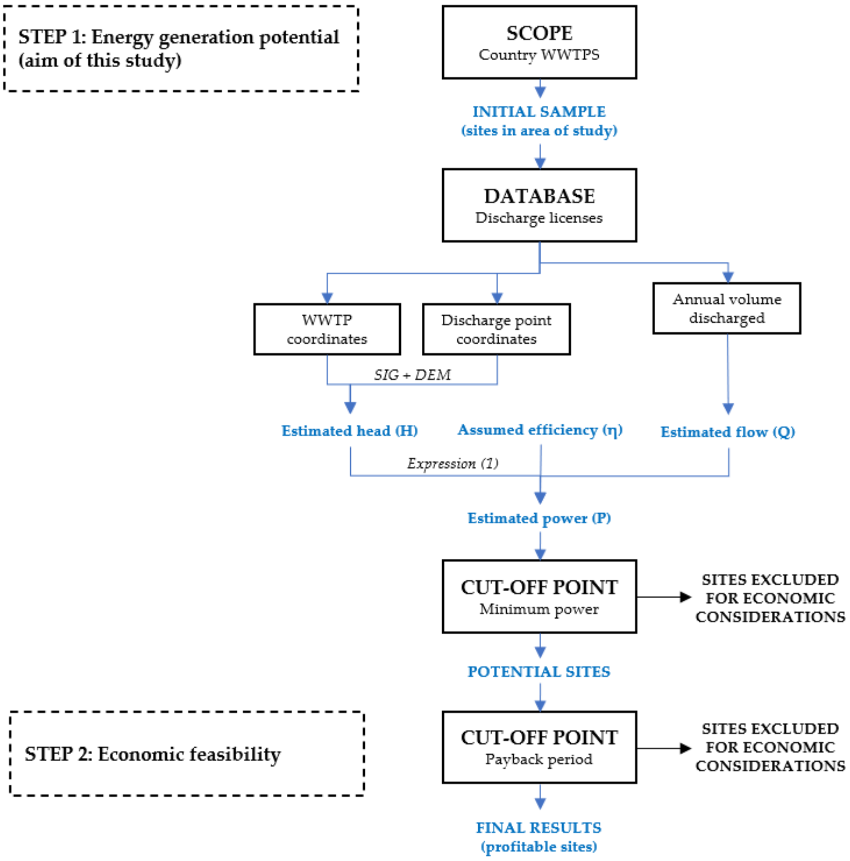

Figure 3.2. *General approach in existing methodologies*

As mentioned, the general process followed in the existing methodologies could be represented as shown in Figure 3.2. 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 2.1.

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 (Power et al., 2014). 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 (3.1) 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 (Gallagher et al, 2015a) they 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 (Power et al., 2017), 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 (Gallagher et al, 2015a, 2019; McNabola et al., 2014), 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. (Bousquet et al., 2017) 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 (Chenal et al, 1995; Llácer-Iglesias et al., 2021a; MHyLab, 2008). As a framework to develop their work, that study included an inventory of 17 existing case 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. (Power et al., 2014) highlighting that in general the results of the methodology should be considered context specific.

More recently in (García et al., 2021) 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 (Mitrovic et al., 2021). As part of the REDAWN project (McNabola et al., 2021), 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 (García et al., 2021). According to the project reports (McNabola et al., 2021), 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 an 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 3.1 shows a summary with the main features of the described methodologies.

Table 3.1. *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 p. <10 years	65% efficiency Kaplan $Q_{design} = 1.3 – 1.5\ Q_{average}$	Power et al 2014
Urban WWTPs (Switzerland)	900	106	19	Power >5–10 kW (gen. >50 MWh/y) Payback period	H_{pot}: GIS, DEM data $Q_{pot} = Q_{average}$ Upstream + Downstream 70% efficiency Pelton (H) + Screw (Q)	Bousquet et al 2017
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 $Q_{pot} = Q_{average}$ 60% efficiency PAT Most H < 10–12 m *	García et al 2021
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 $Q_{pot} = Q_{average}$ 50% efficiency PAT	Mitrovic et al 2021; McNabola et al 2021

3.2.2. Real Case Studies of Hydropower Applied to Wastewater Systems

Following the methodology described in (Llácer-Iglesias et al., 2021a) 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 as “wisdom of practice” (Adams et al., 2012; Bracken et al., 2014). 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 (Llácer-Iglesias et al., 2021a) 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.

3.2.3. Analysis of Methodologies and Comparison with Real Cases

All the methodologies analyzed (Table 3.1) 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 (Ministry for Ecological Transition & Demographic Challenge, 2021; Rodríguez-Villanueva & Sauri, 2021), other regional stakeholders like regional governments also have an important role in the decision-making process (EurEau, 2020). 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 (Gallagher et al., 2015a) 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 (Kehrein et al., 2020b; Llácer-Iglesias et al., 2021a), 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 (Kehrein et al., 2020b).

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 (Bousquet et al., 2017; Power et al., 2014). 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 (3.2), the capacity factors were computed to assess actual performance.

All the obtained data and results are displayed in the Tables in Sections 3.3.1 and 3.3.2, where they are also discussed in comparison with the assumptions made in the analyzed methodologies (Table 3.1).

3.3. Results and Discussion

3.3.1. Analysis of Real Case Studies Profiles

Seeing the limitations to find publicly available data for the wastewater sector (Llácer-Iglesias et al., 2021a; Strazzabosco et al., 2020), and that there could be more existing experience than assumed, the search according to the methodology followed in (Llácer-Iglesias et al., 2021a) was broadened further as described in Section 3.2.2. 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 (Adams et al., 2012; Bracken et al., 2014). 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 3.2. 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 (Bousquet et al., 2017), 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 (Adeyeye et al., 2021; Gallagher et al, 2015a; Llácer-Iglesias et al., 2021a) and that there might be valuable real experience, which has not been evaluated yet and it could be worthwhile to explore further.

Table 3.2. *Inventory of the 49 real case studies of hydropower application to wastewater systems found during this research.*

ID [1]	Case Study	Location [3]	Year [4]	Installed 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	uesnacht-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

Table 3.2. (Cont.)

ID [1]	Case Study	Location [3]	Year [4]	Installed Power (kW)	Range
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.

[5] N/A: Not Available.

Table 3.2 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 3.1.

The different locations show an interest in this technology worldwide, as shown in Figure 3.3, 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 3.2.1, the potential seems to be higher in large cities, which is related to high flow rates. However, as indicated in (Llácer-Iglesias et al., 2021a), most of these WWTPs also use biogas and other technologies such as solar or wind for energy generation.

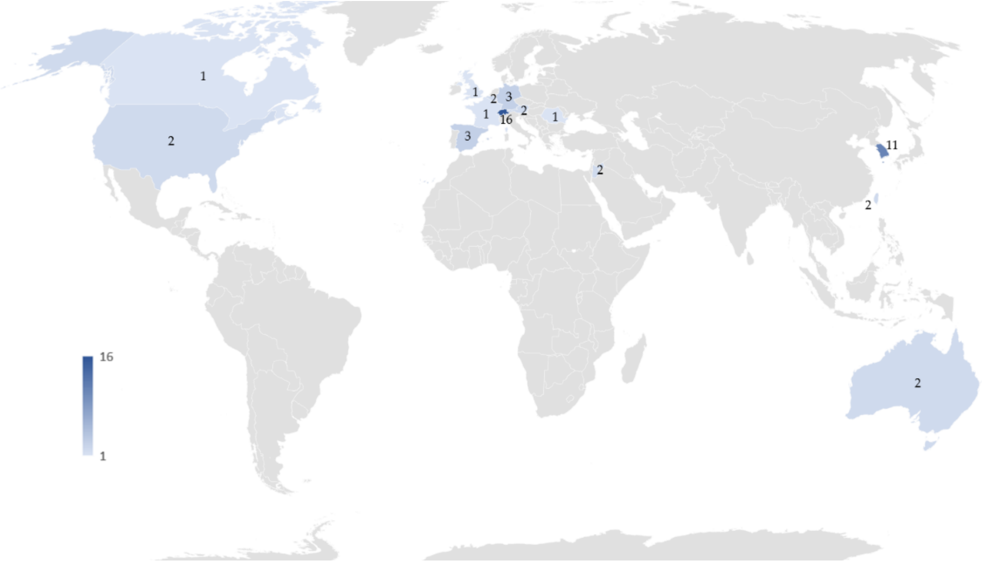

Figure 3.3. *Location of the analyzed case studies (number of sites).*

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 3.4. 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 3.1 (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 (Llácer-Iglesias et al., 2021a; Najar & Persson, 2021; Södergren & Palm, 2021).

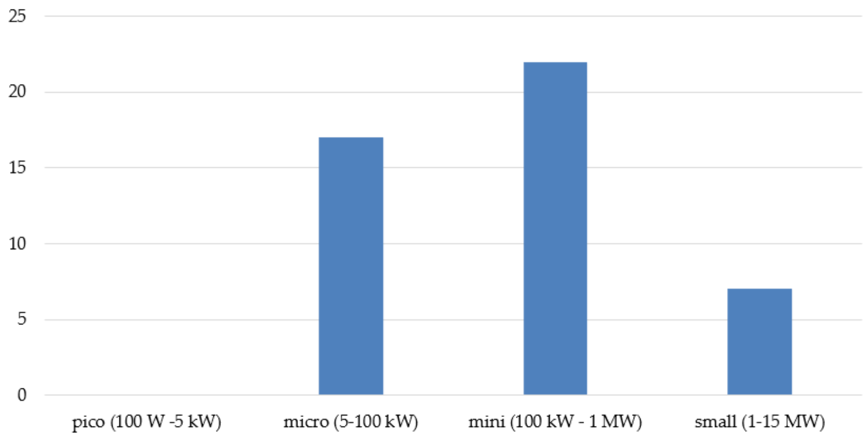

Figure 3.4. *Distribution of hydropower systems size: Number of case studies per size range.*

In addition, the conclusions in previous studies that hydropower potential for this sector certainly is not very high (Bousquet et al., 2017; García et al., 2021; Power et al., 2014), especially when compared with other water systems (McNabola et al., 2021; Mitrovic et al., 2021), or renewable energy technologies (Diaz-Elsayed et al., 2019; Gandiglio et al., 2017; Maktabifard et al., 2018) are confirmed by the absolute figures of installed power.

However, the distribution showed in Figure 3.4 is also consistent with the idea that the installation of hydropower in wastewater systems should mainly be aimed for electricity generation for self-consumption (Llácer-Iglesias et al., 2021a). 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 (Bracken et al., 2014; Williamson et al., 2014).

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 (Ali et al., 2020; Llácer-Iglesias et al., 2021a). That means that, in most cases, hydropower cannot be compared to biogas (Diaz-Elsayed et al., 2019), which clearly present a much higher potential, given that anaerobic processes take place in the plant (Gandiglio et al., 2017; Kehrein et al., 2020b). The real potential of hydropower should be to become a “low-hanging fruit” technology, easy to identify and implement (Bergmann et al., 2017; Llácer-Iglesias et al., 2021a; McNabola et al., 2014).

For that, the full range of technical options of pico-hydro systems might also be explored (Loots et al., 2015; Ramos et al., 2018; Williamson et al., 2014) 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 (Kougias et al., 2019; Loots et al., 2015; Zhou & Deng, 2017). 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 3.2 were found. For the rest of sites, Table 3.3 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 (Bousquet et al., 2017), 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 3.5 shows, the number of existing sites with the hydropower scheme located at the outlet is notably higher and from the individual data in Table 3.3 can be seen that this is the usual option for large plants. However, as observed in Table 3.3 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 3.3), in networks with different municipalities sharing a WWTP.

Table 3.3. *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-Seefeld [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	Aïre	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

Table 3.3. (Cont.)

ID [1]	Case Study	Scheme [3]	Q (m^3/s) WWTP /Design	H (m) Net/Gross	Hydraulic Machine (Number, Type) [4]
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).

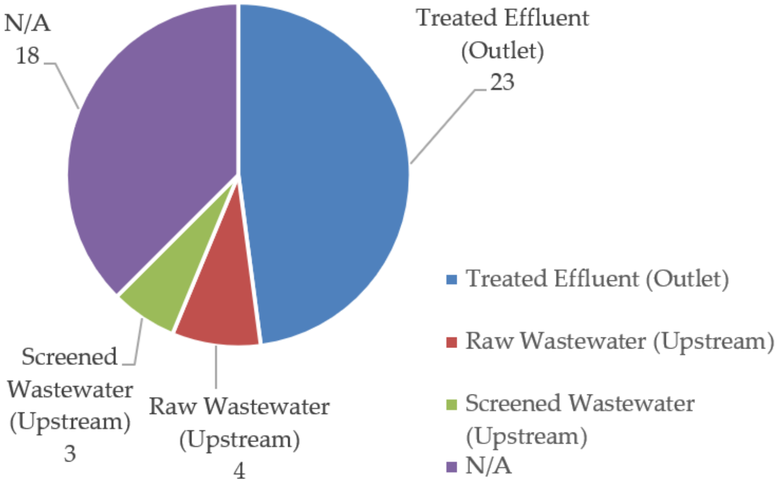

Figure 3.5. *Hydropower scheme location in case studies.*

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 3.3), 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.

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 (Bousquet et al., 2017) and (Power et al., 2014), respectively, summarized in Table 3.1. Considering the different machinery types, their share is plotted in Figure 3.6.

Application of PATs was only found in two sites (ID 7, 10), although most of the cases in Table 3.2 show power figures above the upper limit of 50 kW recommended in (Mitrovic et al., 2021) for the consideration of these machines. Low-head solutions have been grouped, including screws (ID 2, 23) and hydrokinetic turbine (ID 31), although the application of these solutions has been only observed in seven sites, four of them (ID 41–44) of unspecified type.

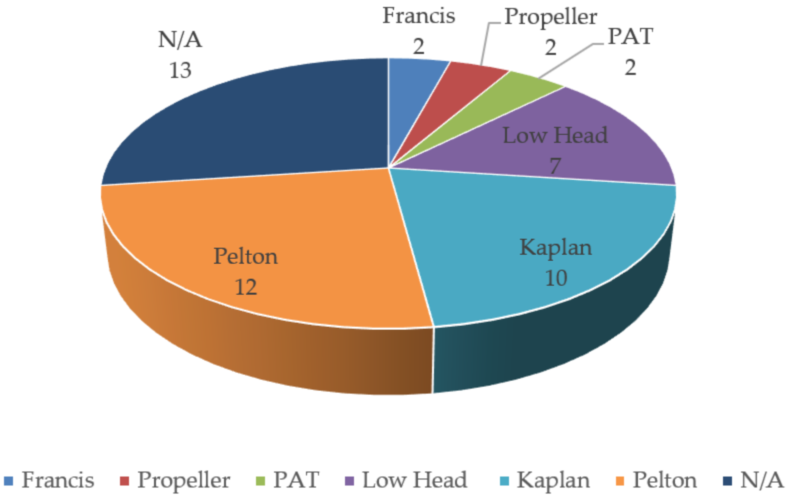

Figure 3.6. *Hydraulic machinery types applied in case studies.*

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 (Jawahar & Michael, 2017; Loots et al., 2015; YoosefDoost & Lubitz, 2020). 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.

3.3.2. 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 (3.2). 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 3.4. 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.

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 3.5. 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 3.4. *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.

Table 3.5. *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 each case study are displayed in Appendix A.

3.3.3. 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 3.7 shows this novel approach. To enable comparisons with the general approach applied in previous methodologies (Figure 3.2), the modifications and new considerations proposed in this study are represented in green for Step 1 and orange for Step 2.

3.3.3.1. 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.

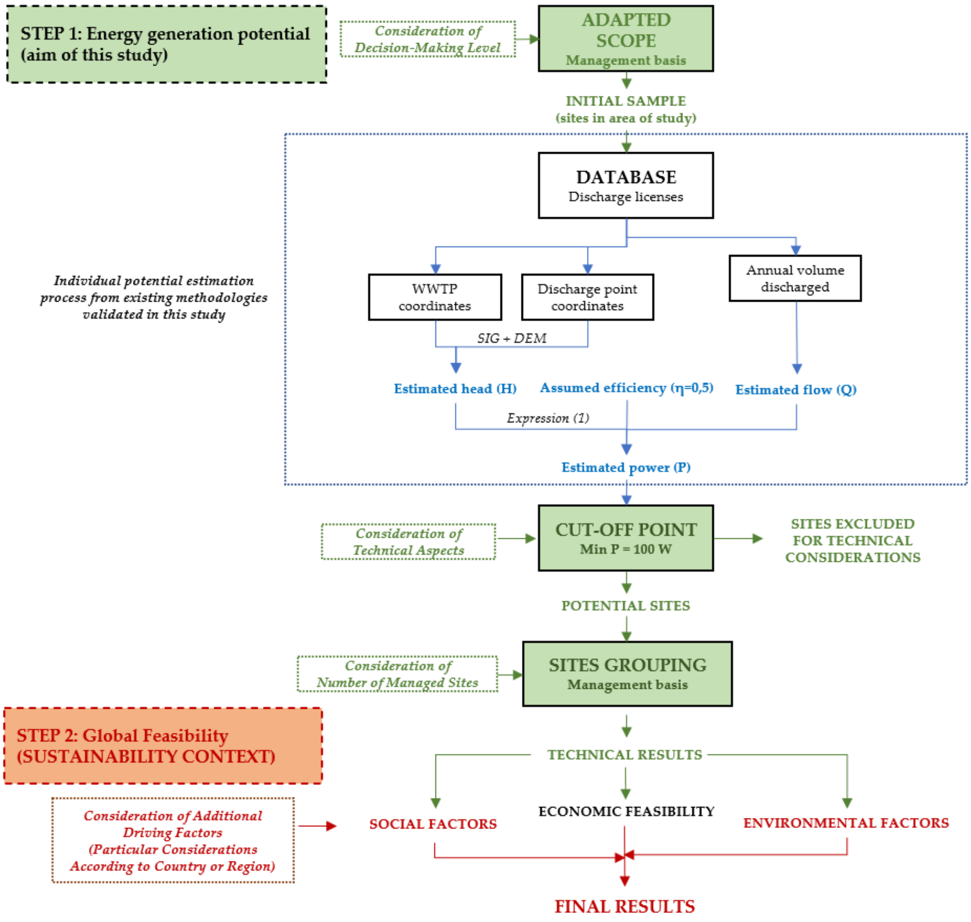

Figure 3.7. *Proposed approach to adapt hydropower assessment methodologies within the sustainability framework.*

3.3.3.2. 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 (European Environment Agency, 2021) 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 3.2, 3.3 and 3.4) and the potential electricity generation estimated with this methodology. These comparisons are shown in Table 3.6.

Table 3.6. *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 each 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 3.3) is higher than detected applying the methodology. In the case of ID 22, as also shown in Table 3.3, 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 3.4.

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.

3.3.3.3. 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 (Gallagher et al, 2015a) and (Llácer-Iglesias et al., 2021a), 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 (Gallagher et al, 2015a; García-López et al., 2021). Therefore, other strategic factors tailored to the surrounding conditions should be regarded too (Adeyeye et al., 2021; Llácer-Iglesias et al., 2021a). 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 (Ali et al., 2020; Capodaglio et al., 2021).

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 (Llácer-Iglesias et al., 2021a) 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 (Llácer-Iglesias et al., 2021a; UN-WWAP, 2017).

3.3.4. 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.

3.4. 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.

Author Contributions

Conceptualization, R.M.L.-I., P.A.L.-J., M.P.-S.; methodology, R.M.L.-I., P.A.L.J., M.P.-S.; writing—original draft preparation, R.M.L.-I.; writing—review and editing, P.A.L.-J., M.P.-S. All authors have read and agreed to the published version of the manuscript.

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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 3.3.

ID Case Study	Sources of Data
1	References: (Choulot et al., 2010, 2012; Diaz-Elsayed et al., 2019; European Environment Agency, 2021; Power et al., 2014)
2	References: (Choulot et al., 2012; European Environment Agency, 2021; Maktabifard et al., 2018) Other sources of data: • Ebswien web page. https://www.ebswien.at/ (accessed 12 April 2021). • EurEau—The European Federation of National Associations of Water Services. “Reducing the Energy Footprint of the Water Sector: Possibilities, Success Stories and Bottleneck”. https://www.eureau.org/resources/briefing-notes/3890-briefing-note-on-reducing-the-energy-footprint-of-water-sector/file (accessed 12 April 2021). • Aqua Fluency Ltd., “Aqua Strategy review: Water utilities—what is your energy strategy?”. https://www.aquastrategy.com/article/aqua-strategy-review-water-utilities-%E2%80%93-what-your-energy-strategy (accessed 12 April 2021). • UNESCO, World Water Assessment Programme. World Water Development Report 2014, Water and Energy. http://www.unesco.org/new/en/natural-sciences/environment/water/wwap/wwdr/2014-water-and-energy/ (accessed 12 April 2021).
3	• Office fédéral de l’énergie OFEN. Confédération suisse. Programme petites centrales hydrauliques. Matthias, R. “Courant Doubs. Turbinage des eaux épurées de la Ville de la Chaux-de-Fonds. Rapport technique”. http://docplayer.fr/66296511-Courant-doubs-turbinage-des-eaux-epurees-de-la-ville-de-la-chaux-de-fonds.html. (accessed 12 April 2021). • Naturelec, S.A. Turbinage des eaux épurées de la STEP de la Chaux-de-Fonds. https://www.google.es/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&ved=2ahUKEwjZvubZ5ojsAhXC8-AKHR5GAGoQFjABegQIAhAB&url=https%3A%2F%2Fwww.rwbgroupe.ch%2Fdocuments%2FshowFile.asp%3FID%3D2790&usg=AOvVaw3EHBIIEqN1mDh8qH6gRsxM. (accessed 12 April 2021). • Arcinfo. “La step de La Chaux-de-Fonds. La step obtient deux certificats de qualité et ouvre ses portes”. https://www.arcinfo.ch/articles/regions/montagnes/la-step-obtient-deux-certificats-de-qualite-et-ouvre-ses-portes-89016 (accessed 12 April 2021). • MHYLAB web page. http://www.mhylab.com/home.php (accessed 12 April 2021).

ID Case Study	Sources of Data
4	References: (Bousquet et al., 2017; Chenal et al.,1995; Choulot et al., 2010, 2012; Diaz-Elsayed et al., 2019; Power et al., 2014) Other sources of data: • MHYLAB web page. http://www.mhylab.com/home.php (accessed 12 April 2021). • Independent suisse scientific web-log. http://www.entre-lemanetjura.ch/BLOG_WP_351/wp-content/uploads/2018/04/2018.04-06-RPC-publication.xlsx (accessed 23 January 2021). • Swiss Federal Office of Energy. “Statistics of hydroelectric installations in Switzerland”. https://www.bfe.admin.ch/bfe/en/home/supply/renewable-energy/hydropower.html (accessed 23 January 2021).
5	References: (Bousquet et al., 2017; Chenal et al.,1995; MHyLab, 2008) Other sources of data: • Swiss Federal Office of Energy. “Statistics of hydroelectric installations in Switzerland”. https://www.bfe.admin.ch/bfe/en/home/supply/renewable-energy/hydropower.html (accessed 23 January 2021).
6	References: (Bousquet et al., 2017; MHyLab, 2008) Other sources of data: • MHYLAB web page. http://www.mhylab.com/home.php (accessed 12 April 2021). • Swiss Federal Office of Energy. “Statistics of hydroelectric installations in Switzerland”. https://www.bfe.admin.ch/bfe/en/home/supply/renewable-energy/hydropower.html (accessed 23 January 2021).
7	References: (Bousquet et al., 2017; Canton de Vaud, 2018; Chenal et al.,1995; Choulot et al., 2010, 2012; Diaz-Elsayed et al., 2019; MHyLab, 2008; Power et al., 2014)
8	References: (Canton de Vaud, 2018) Other sources of data: • MHYLAB web page. http://www.mhylab.com/home.php (accessed 12 April 2021). • Independent suisse scientific web-log. http://www.entre-lemanetjura.ch/BLOG_WP_351/wp-content/uploads/2018/04/2018.04-06-RPC-publication.xlsx (accessed 23 January 2021). • Services Industriels de Terre Sainte et Environs. “Rapport de Gestion 2018”. https://docplayer.fr/156112495-Rapport-de-gestion-2018-services-industriels-de-terre-sainte-et-environs.html (accessed 23 January 2021).
9	References: (Bousquet et al., 2017) Other sources of data: • MHYLAB web page. http://www.mhylab.com/home.php (accessed 12 April 2021). • Independent suisse scientific web-log. http://www.entre-lemanetjura.ch/BLOG_WP_351/wp-content/uploads/2018/04/2018.04-06-RPC-publication.xlsx (accessed 23 January 2021). • HÄNY web page. https://www.haeny.com/(accessed 12 April 2021).
10	• HÄNY web page. https://www.haeny.com/(accessed 12 April 2021).
11	References: (Bousquet et al., 2017) Other sources of data:

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Chapter 4
Publication III

“Exploring Options for Energy Recovery from Wastewater: Evaluation of Hydropower Potential in a Sustainability Framework”

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Abstract

Current energy demand for wastewater treatment is very high and expected to increase in the next decade. As climate change poses a challenge too, renewable energy options for this industry are needed. Studies for hydropower assessment addressed to governance stakeholders have shown that some mechanical energy might be recovered from wastewater. However, none of them applied a sustainability approach. Neither the decision-making level was considered. The objective of this work is to present a methodology, developed and applied to a case study, with a novel approach, including all these considerations. After analyzing the context in the region of study, the proposed methodology includes all three dimensions of sustainability: economic, environmental, and social. Firstly, the methodology was applied to a group of 186 plants, selected according to their management model. Based on technical feasibility, 34 potential sites were identified. Secondly, to obtain the sustainability perspective, a survey of suitable criteria was conducted. Then, a multi-criteria method, aligned with existing governance guidelines, was proposed and applied. The results show that, in a sustainability framework, hydropower might be an interesting option to consider for the decarbonization of wastewater systems. Based on this study, stakeholders could directly design decision-making methodologies adapted to their context.

Keywords

Renewable energy systems evaluation; hydropower potential assessment; multi-criteria decision-making methods; decarbonization roadmaps of water systems; urban wastewater planning; sustainable wastewater governance

4.1. Introduction

As part of the Sustainable Development Goals (SDGs) established in the 2030 Agenda, providing clean water and sanitation (SDG-6) and affordable and clean energy (SDG-7) are two important challenges to face within the next decade (Delanka-Pedige et al., 2021). The foreseen growth in population may increase the demand for water by 50%, and therefore, the need for wastewater treatment worldwide (Araya & Vasquez, 2022; Qiu et al., 2022; UN-WWAP, 2017). Since this is a very energy-intensive process (Qiu et al., 2022), urban wastewater planners will need sustainable solutions to reduce the associated carbon footprint (Capodaglio & Olsson, 2020; Lu et al., 2015; Negi & Chandel, 2022; Shin et al., 2022).

Improvement of energy efficiency and generation of renewable energy are both necessary actions in the decarbonization roadmaps of wastewater systems (Ghimire et al., 2021; Ma et al., 2022; Nakkasunchi et al., 2021). Renewable energy can be generated on-site from external sources (solar or wind), or recovered from wastewater. Recovery for electricity generation includes chemical and mechanical energy (Huang et al., 2022; Ma et al., 2022; Neugebauer et al., 2022). Chemical potential is large, and combined heat and power (CHP) generation from biogas is often the most popular option (Maktabifard et al., 2018; McCarty et al., 2011; Shin et al., 2022; Vazquez Alvarez & Buchauer, 2014). Nevertheless, its application is limited to plants with anaerobic processes, which usually only take place in the largest sites (Gandiglio et al., 2017; Tchobanoglous et al., 2014). Ongoing research in other technologies, like microbial fuel cells or biodiesel from microalgae, is promising (Elhenawy et al., 2022; Fetanat et al., 2021; Gao et al., 2014; Maktabifard et al., 2018), but market-ready solutions should be considered to start acting in the short-term (Bertoldi, 2022).

To conduct an informed assessment, all mature technologies for renewable energy generation at wastewater treatment plants (WWTPs) should be explored. These include biogas, solar, and wind, and most studies of hybrid solutions and assessment tools for this industry, consider combinations of them (Llácer-Iglesias et al., 2021a; Maktabifard et al., 2018). However, although hydropower is also a mature technology, it is seldom regarded as an option in these tools. Certainly, hydropower potential is not comparable to CHP, but in most countries, the number of WWTPs with biogas potential is low. For instance, in the USA, only 8.3% of plants generate biogas (Scarlat et al., 2018). In Europe, an analysis of 26,889 plants showed that 19.1% were suitable for biogas generation (Gandiglio et al., 2017), although, in some countries, like Spain, it would only be feasible at 5.6% (Ministry for Ecological Transition & Demographic Challenge, 2021). In this context, mechanical energy recovery from wastewater might be another option to explore in the design of decarbonization roadmaps. However, the lack of awareness of wastewater stakeholders about the potential of this technology hinders its application (Kretschmer et al., 2018; Llácer-Iglesias et al., 2021a; Quaranta et al., 2022).

Against this background, the motivation of this research is to establish a suitable bridge between the tools available for wastewater stakeholders to assess renewable energy options and, hydropower assessment methodologies addressed to governance stakeholders. Thus, the main aim of this study is to present a methodology for hydropower potential assessment in wastewater systems, with a novel approach, integrating the 3 dimensions of sustainability in the evaluation process. To achieve that aim, this research included the following objectives:

- To analyze the context. The methodology consists of 2 steps, and in both, the integration into the existing context was considered a crucial issue for effective real application. Firstly, to determine the decision-making level for energy strategies and the sample of sites to evaluate, as suggested in Llácer-Iglesias et al. (2021b). Secondly, to identify the main stakeholders and governance guidelines, at the same level or higher, and align the methodology with the management framework.

- To identify sustainability criteria from existing literature on multi-criteria decision analysis (MCDA), and develop a method that can be integrated into the existing governance model in the region.
- To apply the complete methodology to a case study, so it can serve as a model for future applications in other contexts.

4.2. Literature Review

Academic research to assess hydropower potential in wastewater systems has been mainly applied at two levels, either at an individual level, like a plant (Ak et al., 2017; Chae & Kang, 2013; Guzmán-Avalos et al., 2023; Loots et al., 2015), or a building (Walker & Duquette, 2022), or at a country level (Bekker et al., 2022; Bousquet et al., 2017; García et al., 2021; Mitrovic et al., 2021; Power et al., 2014; Punys & Jureviˇcius, 2022). This research focuses on the latter group, studies developing methodologies addressed to governance stakeholders of wastewater systems, such as policy makers, urban planners or decision-makers.

To design methodologies for hydropower assessment, a different approach was proposed in Llácer-Iglesias et al. (2021b). This study suggests the consideration of the decision-making level to define the scope of the study, and the evaluation of sites as a group to benefit from possible economies of scale. However, even though that article proposes a methodology for technical potential assessment, with a new perspective compared to all the others, it does not include the application of their research to a case study.

Moreover, these methodologies focus on technical assessment and economic feasibility, whereas nowadays, there is no doubt that the triple-bottom-line approach in decision-making processes is necessary to reach the SDGs (An et al., 2017; Starkl et al., 2022; Sueyoshi et al., 2022). Only the method in Punys and Jureviˇcius (2022) includes some environmental considerations, but it does not consider the necessary social dimension for a sustainable approach (Adeyeye et al., 2021, 2022; Helgegren et al., 2021; Muhammad Anwar et al., 2021). Besides, the method is applied to a pre-selected small group of only eight sites, for prioritization within the group. So, the scope is very limited, and the objective is different from the other studies. The results of the research in Llácer-Iglesias et al. (2021b) do suggest the consideration of all 3 pillars of sustainability, but no specific methodology following the technical assessment is developed in their article. In this context, Table 4.1 summarizes the research gap identified in the current research framework, which is addressed in this study. As a novelty, to the best of the authors' knowledge, this study is the first to develop and apply a MCDA method to assess the potential of hydropower, considering the specific governance context of the area of study, and all 3 dimensions of sustainability. This new modeling framework is shown in Fig. 4.1, with an overview of the complete methodology.

Table 4.1. *Relevant academic studies on methodologies for hydropower potential assessment of wastewater systems addressed to urban wastewater governance stakeholders.*

Ref.	**Dimensions of sustainability considered in the methodology**			**Case study applied**		
	Economical	**Environmental**	**Social**	**Objective and scope**	**Country / Region**	**Management model considered in scope selection**
(Power et al., 2014)	√	-	-	Global assessment at a country level	Ireland, UK	-
(Bousquet et al., 2017)	√	-	-	Global assessment at a country level	Switzerland	-
(Mitrovic et al., 2021)	√	-	-	Global assessment at a country level	Ireland, N. Ireland, Wales, Scotland, Spain, Portugal	-
(García et al., 2021)	√	-	-	Global assessment at a country level	Spain	-
(Llácer-Iglesias et al., 2021b)	√	-	-	-	-	-
(Bekker et al., 2022)	√	-	-	Global assessment at a country level	South Africa	-
(Punys & Jurevičius, 2022)	√	√	-	Prioritization ranking at a country level	Lithuania	-
This study	√	√	√	**Global assessment at decision-making level**	**Valencia Region (Spain)**	√

Note: The technical assessment is included within the economical dimension.

4.3. Materials and methods

4.3.1. Methodology overview

Fig. 4.1. shows an overview of the methodology, based on the approach suggested by Llácer-Iglesias et al. (2021b).

- Step 1 estimates the technical potential of each plant. Unlike the other studies shown in Table 4.1., sites are selected according to technical feasibility instead of economic criteria. This step is based on the method presented in Llácer-Iglesias et al. (2021b), but in the present paper, it is applied to a case study for the first time.

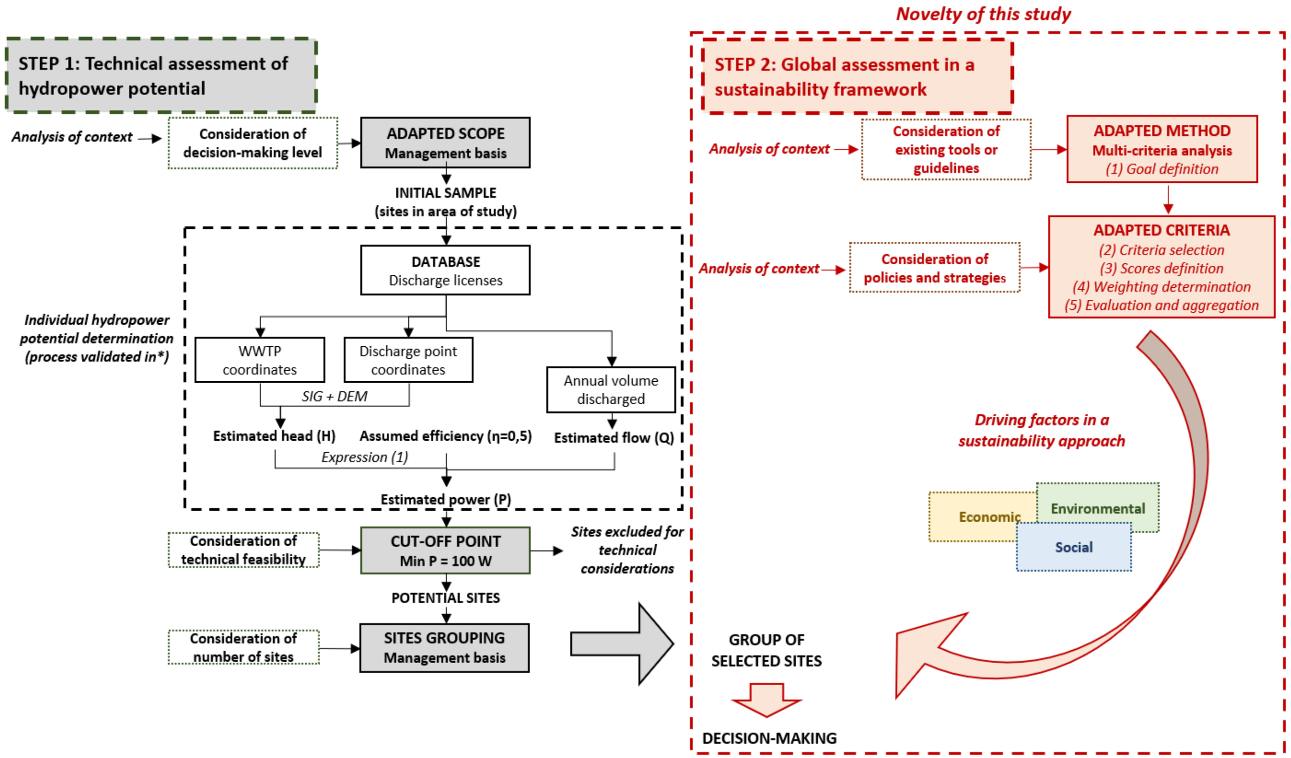


Figure 4.1. *Methodology overview, adapted from (Llácer-Iglesias et al., 2021b) (*)*

- Step 2 presents a novel approach, introducing technical-economic, environmental, and social factors, to evaluate the obtained results with a sustainability perspective. In the present manuscript, Step 1 is summarized in Section 4.3.2, and a methodology for Step 2 is proposed by developing a MCDA method in Section 4.3.3, according to the sustainability concept (Oliveira Neto et al., 2018). Then the methodology is applied to a case study in Spain as described in Section 4.4.

4.3.2. Hydropower potential determination (Step 1)

The management model is an important factor to consider in studies evaluating options for wastewater systems (Araya & Vasquez, 2022; Helgegren et al., 2021). One of the novel aspects proposed in Llácer-Iglesias et al. (2021b), was to identify the decision-making level to decide the scope of the study, i.e., the sample of sites to analyze as a group, taking advantage of possible economies of scale. To provide suitable tools is crucial to define at which level this process takes place (Ma et al., 2022; Mirabi et al., 2014).

Then, as in all the methodologies in Table 4.1., for each site, the hydropower potential can be determined as:

$$P = \rho \cdot g \cdot Q \cdot H \cdot \eta \qquad (4.1)$$

where P is the power (W), ρ water density (kg/m^3), g acceleration due to gravity (m/s^2), Q volume flow rate (m3/s), H available head (m), and η overall efficiency. Using a Digital Elevation Model (DEM) and Geographic Information Systems (GIS), from the UTM coordinates of the WWTP and the discharge point, an approximate value for the H at each site can be estimated, as the difference in elevation between these points. From basin organisms' reports, the annual volume of the effluent discharged can be used to estimate the Q, assuming 24 h/day, 365 days/year. (Llácer-Iglesias et al., 2021b) suggests a conservative value of 0.5 for the overall efficiency, and a cut-off point based on technical feasibility. So, to be considered as a potential site, the obtained power should be P>100 W. This approach was applied in this study as well, in contrast with the other methodologies in Table 4.1., where the threshold is established in 2 kW (or 5 kW), based on economic feasibility only.

4.3.3. Multi-criteria analysis in a sustainability framework (Step 2)

Multi-criteria decision-making methods (MCDM) are popular techniques applied in multiple situations, including policy-making, planning, design, and management projects. There is a wide range of methods, for different purposes, with different objectives and complexities (Munasinghe-Arachchige et al., 2020).

Regarding the scope of this study, there is extensive literature describing the application of MCDM to WWTPs (Ling et al., 2021; Lizot et al., 2021; Saghafi et al., 2019; Salamirad et al., 2021; Srivastava & Singh, 2021; Torregrosa et al., 2017), or renewable energy systems (RES) (da Ponte et al., 2021; Ilbahar et al., 2019; Lee & Chang, 2018; Li et al., 2020; Shao et al., 2020; Sueyoshi et al., 2022; Vlachokostas et al., 2021; Wang et al., 2009). Some studies already evaluated energy recovery from WWTPs, but they focus on chemical and/or thermal energy, so mechanical energy (hydropower) is not included (Liu et al., 2021; Sucu et al., 2021). Some applications optimize the design of energy hybrid systems for WWTPs using specific software, like HOMER. However, that goal is different from the aim of this study, in a further stage of the decision-making process (Buller et al., 2022; Fetanat et al., 2021; Nguyen et al., 2020; Puleo et al., 2017).

Few studies have applied MCDA to evaluate the application of hydropower to WWTPs, nevertheless, with a different scope and without the sustainability approach. They focused only on one (Ak et al., 2017) or a few pre-selected plants (Punys & Jureviˇcius, 2022), with a different purpose and objectives, and none of them considered the management model, nor the social dimension. However, these studies provide important considerations for the subsequent design stage. For example, concerning the oscillations of flow rate, and the level in the receiving water body (Guzmán-Avalos et al., 2023; Punys & Jureviˇcius, 2022).

MCDM methods usually consist of the following steps: (1) goal definition, (2) criteria selection, (3) criteria scores definition, (4) weighting determination, (5) evaluation and aggregation. Depending on the objective, several techniques can be applied.

In this context, the first objective in this step was to select a suitable MCDM method, and suitable sustainability criteria, to incorporate considerations of the 3 dimensions into the assessment process (An et al., 2017; Oliveira Neto et al., 2018; Sucu et al., 2021). Since in this study, the integration into the existing management framework is considered a key issue, an analysis of the context in the region being evaluated is a necessary preliminary step, to select both, the method and the criteria to be applied. This part of the method, tailored to the case study presented in this article as an example, is described in Section 4.4.

4.3.3.1.MCDA method selection

(1) Goal definition

To select the method is necessary to bear in mind the goal to achieve (Munasinghe-Arachchige et al., 2020). One of the main objectives of this study was to propose a translatable methodology that can be directly applied by stakeholders (Feiz & Ammenberg, 2017). Hence, the selected method should fulfill the following requirements: low complexity, flexibility to enable extrapolation to other case studies, no need for specialized skills or specific software, and flexibility to be modified under changes in circumstances (Cossio et al., 2020; Smith et al., 2022; Woltersdorf et al., 2018). Another important issue is that the aim of this step, is to evaluate a number of plants as a group, not individually.

As mentioned, the possibility of integration into existing management tools was also considered a key point for an effective application (Sherman et al., 2020; Smith et al., 2022). So, an analysis of the context seemed necessary in this step too, to identify wastewater governance guidelines, both, at the decision- and the policy-making level.

According to all these requirements, the weighted sum method (WSM) or simple additive weighting (SAW) was selected as the basis to develop the methodology, tailored for the case study in this research. The specific details are described in Section 4.4.

WSM is a widely used MCDA method, and the simplest one (Johannesdottir et al., 2021; Ling et al., 2021; Omran et al., 2021; Srivastava & Singh, 2021; Vlachokostas et al., 2021; Zimmermann et al., 2018). A global score for the scenario or alternative being evaluated can be obtained with the following expression:

$$AV = \sum_{i=1}^{n} w_i \; x_{ij} \qquad (4.2)$$

Where AV is the global score as an aggregate value, n is the number of criteria, w weighting for each criterion i, and x the corresponding score for scenario j. Even though this method presents important limitations, this choice was consistent with the results obtained after analyzing the context, for the case study in this research. Beyond the Spanish scope, other decision-making guidelines addressed to wastewater stakeholders have been proposed, also applying SAW methods, such as in Brault et al. (2022). Nevertheless, in other contexts, with no existing guidelines from the wastewater governance organisms, other MCDA methods, such as PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) or ELECTRE (Elimination Et Choix Traduisant la Realite), might be more appropriate for this application.

4.3.3.2. Sustainability criteria application

According to the approach of this research, it was considered important to also align the remaining steps of the methodology with the existing guidelines for wastewater governance, adapted to the energy focus. The specific application to the Spanish context is described in Section 4.4. Nevertheless, there are some general considerations at each step that would be applicable when extrapolating the process to another context.

(2) Criteria selection

Firstly, a review of relevant literature was conducted, with a focus on MCDA applications. Thus, articles applying MCDA methods to WWTPs and/or to RES were searched and screened. All the sustainability criteria considered in those studies were extracted. Then, the criteria that could also be applied in this methodology, were summarized in 2 tables, which are provided as supplementary materials (Appendix B).

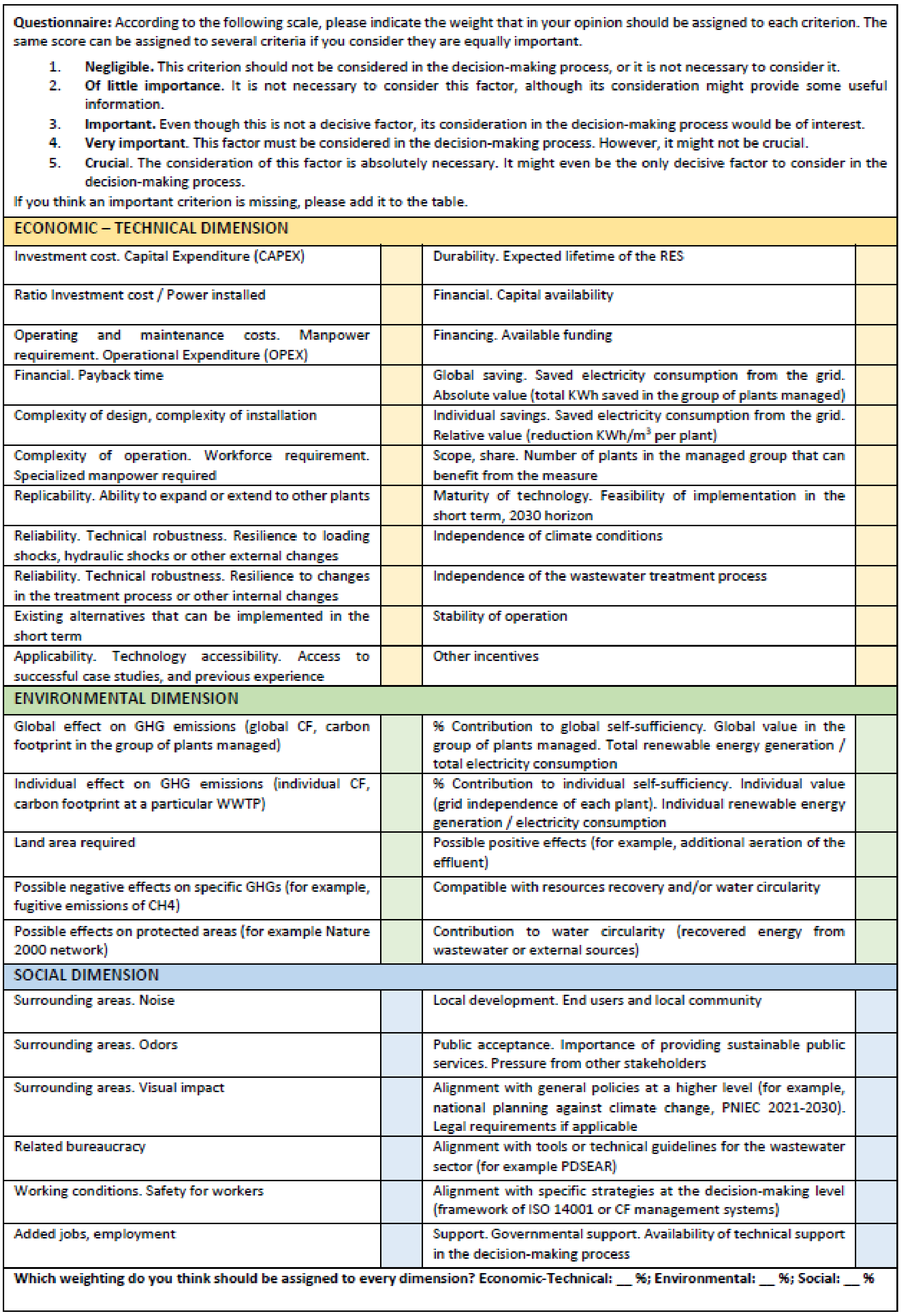
Secondly, this information was aggregated in a questionnaire, with a range of possible factors to be ranked with a Likert scale. As suggested in some studies (Kamble et al., 2017; Delanka-Pedige et al., 2021), it was designed to gather the opinion of the main stakeholders, so some contributions from the authors were added, regarding the proposed approach and scope of this study. Fig. 4.2. shows this questionnaire, which could be used to develop similar ones in other contexts.

Thirdly, the questionnaire was sent to some stakeholders of interest. The results from the preliminary analysis of the context had already identified the stakeholders to consider. The stakeholders selected to send the questionnaire, were those working in wastewater governance organizations in the region of study. They were selected according to their experience in urban wastewater management in the area, including the group of analyzed plants. As a key factor, they had to be directly involved in any stage of the decision-making process for the implementation of energy strategies at the WWTPs in the region. The results obtained from the questionnaires are described in Section 4.4.3.

Finally, the proposed criteria (see Section 4.4.3.1 and Fig. 4.6) were selected according to the following items: maximum alignment with the existing governance guidelines, relevance in the regional context, representativeness within the dimension, consistency with the questionnaires, availability of data, and indicators easy to obtain. As suggested by some authors (Neugebauer et al., 2022), for the purpose of this study, the aim was to define 3–4 criteria per dimension, which also followed the model in the guidelines.

(3) Criteria scores definition

For the same reasons as above, a three-level scale was proposed to rank every criterion, according to 3 possible levels of priority (see Section 4.4.3.1, Figs. 4.7, 4.8 and 4.9). The highest priority receives a score of 3, and the lowest a score of 1. Some of the scales were suggested for the specific case, but they could be easily adapted to others.



Questionnaire: According to the following scale, please indicate the weight that in your opinion should be assigned to each criterion. The same score can be assigned to several criteria if you consider they are equally important.

1. **Negligible.** This criterion should not be considered in the decision-making process, or it is not necessary to consider it.
2. **Of little importance.** It is not necessary to consider this factor, although its consideration might provide some useful information.
3. **Important.** Even though this is not a decisive factor, its consideration in the decision-making process would be of interest.
4. **Very important.** This factor must be considered in the decision-making process. However, it might not be crucial.
5. **Crucial.** The consideration of this factor is absolutely necessary. It might even be the only decisive factor to consider in the decision-making process.

If you think an important criterion is missing, please add it to the table.

ECONOMIC – TECHNICAL DIMENSION			
Investment cost. Capital Expenditure (CAPEX)		Durability. Expected lifetime of the RES	
Ratio Investment cost / Power installed		Financial. Capital availability	
Operating and maintenance costs. Manpower requirement. Operational Expenditure (OPEX)		Financing. Available funding	
Financial. Payback time		Global saving. Saved electricity consumption from the grid. Absolute value (total KWh saved in the group of plants managed)	
Complexity of design, complexity of installation		Individual savings. Saved electricity consumption from the grid. Relative value (reduction KWh/m^3 per plant)	
Complexity of operation. Workforce requirement. Specialized manpower required		Scope, share. Number of plants in the managed group that can benefit from the measure	
Replicability. Ability to expand or extend to other plants		Maturity of technology. Feasibility of implementation in the short term, 2030 horizon	
Reliability. Technical robustness. Resilience to loading shocks, hydraulic shocks or other external changes		Independence of climate conditions	
Reliability. Technical robustness. Resilience to changes in the treatment process or other internal changes		Independence of the wastewater treatment process	
Existing alternatives that can be implemented in the short term		Stability of operation	
Applicability. Technology accessibility. Access to successful case studies, and previous experience		Other incentives	
ENVIRONMENTAL DIMENSION			
Global effect on GHG emissions (global CF, carbon footprint in the group of plants managed)		% Contribution to global self-sufficiency. Global value in the group of plants managed. Total renewable energy generation / total electricity consumption	
Individual effect on GHG emissions (individual CF, carbon footprint at a particular WWTP)		% Contribution to individual self-sufficiency. Individual value (grid independence of each plant). Individual renewable energy generation / electricity consumption	
Land area required		Possible positive effects (for example, additional aeration of the effluent)	
Possible negative effects on specific GHGs (for example, fugitive emissions of CH4)		Compatible with resources recovery and/or water circularity	
Possible effects on protected areas (for example Nature 2000 network)		Contribution to water circularity (recovered energy from wastewater or external sources)	
SOCIAL DIMENSION			
Surrounding areas. Noise		Local development. End users and local community	
Surrounding areas. Odors		Public acceptance. Importance of providing sustainable public services. Pressure from other stakeholders	
Surrounding areas. Visual impact		Alignment with general policies at a higher level (for example, national planning against climate change, PNIEC 2021-2030). Legal requirements if applicable	
Related bureaucracy		Alignment with tools or technical guidelines for the wastewater sector (for example PDSEAR)	
Working conditions. Safety for workers		Alignment with specific strategies at the decision-making level (framework of ISO 14001 or CF management systems)	
Added jobs, employment		Support. Governmental support. Availability of technical support in the decision-making process	

Which weighting do you think should be assigned to every dimension? Economic-Technical: __ %; Environmental: __ %; Social: __ %

Figure 4.2. *Questionnaire elaborated to gather stakeholders' preferences about criteria to be considered in the decision-making process, to install renewable energy technologies at wastewater treatment plants (WWTPs). Elaborated by the authors after the analysis of the MCDA studies summarized in the tables provided as supplementary materials.*

(4) Weighting determination

The weights to be assigned to each criterion and dimension should be defined by the preferences of the stakeholders involved in the decision-making process (Sueyoshi et al., 2022). According to Mirabi et al. (2014), if there is no available information, a good approach according to the literature is an equal distribution, among dimensions, and within each dimension. In this study, both, the guidelines and the results of the questionnaires confirmed that this equal distribution was the most suitable approach. To assess the robustness of this decision, a sensitivity analysis was conducted as shown in Section 4.4.4.

(5) Evaluation and aggregation

Applying expression (4.2), an aggregate value of priority can be obtained for each scenario evaluated. The AV values range between 1 and 3 and applying a percentual distribution, the highest priority corresponds to AV≥2.3 and the lowest to AV≤1.6. This equal distribution for all aspects is proposed in the guidelines model. In this case, as a three-level scale is applied, a share of 33,33% of the possible range of scores is assigned for each level of priority.

4.4. Results and discussion

4.4.1. Case study

The application of the complete methodology to a selected case study in Spain illustrates an example of how to develop a tailored methodology with the proposed approach, in order to be integrated into the particular context. In this country, a governance instrument was published in 2021 (Ministry for Ecological Transition & Demographic Challenge, 2021), including procedures and methodologies to strive for the objectives of the Spanish hydrological management plans, according to the European Directive.

This governance instrument, known as PDSEAR in Spanish (Plan for Wastewater Treatment, Sanitation, Efficiency, Savings and Reuse from the Spanish Ministry), provided the basic framework to develop the model presented in this study. Thus, these guidelines determined all the choices made during this research.

4.4.1.1. Case study description

In Spain, the national government is responsible for proposing and implementing water policies. Additionally, local administrations (individual or associated municipalities) and provincial councils are responsible for wastewater systems, although several regional governments have assumed some competencies too. In this context, the national framework provides the guidelines, but studies for effective implementation of RES should consider the regional level (Ma et al., 2022; Ministry for Ecological Transition & Demographic Challenge, 2021).

In this study, the Valencia Region on the Spanish Mediterranean coast was selected. The region consists of 3 provinces (Castellón, Valencia, and Alicante), with 487 WWTPs (EPSAR, 2022). In the 1990s the regional regulations assigned all wastewater competencies to the regional administration, including planning and coordination, and operation of WWTPs. Since then, the Valencian Wastewater Treatment Agency (EPSAR) has been very active and nowadays, the Valencia Region shows a high level of compliance with the European regulation (Ministry for Ecological Transition & Demographic Challenge, 2021). Another special feature of the management in this region, is that there are 3 types of financing models, namely direct, ordinary, or via agreement. With direct financing, the plants are directly managed by EPSAR, whereas with the other 2 models, the municipalities and the provincial councils are also important stakeholders (EPSAR, 2022). Additionally, the whole region is divided in 7 areas, and the technical performance of all WWPTs in each area is thoroughly monitored by an external company of urban wastewater experts.

Concerning the implementation of RES, the region is also very active. Last year 39,590,149 kWh were generated by the 18 WWTPs that have CHP, and 1,452,177 kWh by other 18 WWTPs with photovoltaic systems. This renewable energy generation enabled the WWTPs in the region to achieve a global self-sufficiency (renewable energy generated / energy consumed) of 21.1% (EPSAR, 2022). According to national and regional policies to tackle climate change, further actions for the decarbonization of the Valencian wastewater sector are planned in the short term. In 2022 two further actions for the implementation of photovoltaic systems have been projected, since the Valencian climate is very favorable for solar energy generation (Tovar-Facio et al., 2021). One project plans the implementation in 4 plants in Alicante, 33 in Valencia, and 23 in Castellón, with a foreseen yearly generation of 1,152,340 kWh, 748,560 kWh, and 293,402 kWh respectively (Generalitat Valenciana, 2022a). The other plans the implementation of photovoltaic systems in a few WWTPs out of a group of 44 in Alicante (RETEMA, 2022), and according to the projected power, the generation could be estimated at about 250,000 kWh/year. Both these groupings correspond to a single type of financing, so this was the management scope finally decided to select the sample of the study.

Thus, the initial sample to analyze in this study applying the proposed methodology consists of 186 WWTPs in the Region of Valencia, whose management model corresponds to the direct financing type.

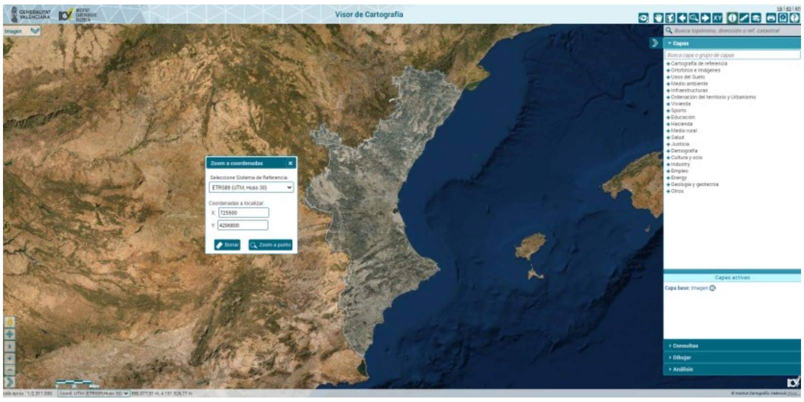
4.4.1.2. Case study data

Detailed data for each WWTP are publicly available on the EPSAR´s website, including design characteristics and reports on their annual performance (EPSAR, 2022). The data processed for this study were: location (UTM coordinates), municipalities served, size (volume and load), type of treatment (anaerobic processes or not), electricity consumption, renewable energy generation, and type of discharge (discharge into water bodies, ground or sea, or use of the reclaimed water for irrigation).

The data for the corresponding discharge points were extracted from the annual reports available on the 2 basin agencies' websites, namely Jucar and Segura (CHJ, 2022; CHS, 2022). The data processed were: location (coordinates), volume discharged, and receiving water body.

To estimate H, the procedure in Section 4.3.2 was applied, using a geovisualization tool specific from this region, available on the Valencian Cartographic Institute's website (ICV, 2022) as shown in Fig. 4.3(a). Introducing the coordinates of any point, the tool directly provides the elevation at this point. So, the elevations for the WWTP (b), and the corresponding discharge point (c) were obtained, and the distance between both points was measured (d). All estimations were conservative and strict, applying the minimum difference between the accurate coordinates of the discharge point, and the lowest elevation at the WWTP. Nevertheless, as part of the sensitivity analysis conducted at the final stage of the study (see 4.4.4), in all cases, the elevations of several points in the surrounding area were also examined, exploring the effects of modifying the discharge point on the available head. The rest of the data used in Step 2 for the evaluation of the criteria were extracted from several Spanish government's official websites.

a)



Zoom a coordenadas

Seleccione Sistema de Referencia: ETRS89 (UTM, Huso 30)

Coordenadas a localizar:

X: 725500

Y: 4296800

(b)

Coordenadas UTM (ETRS89, huso 30)
Altitud ortométrica referida al NMM en Alicante

X	716.347,01 m
Y	4.319.778,8 m
H	79,95 m

(c)

Coordenadas UTM (ETRS89, huso 30)
Altitud ortométrica referida al NMM en Alicante

X	716.355,68 m
Y	4.319.784,6 m
H	75,92 m

(d)

Seleccione unidades de medida: metros

Resultados
Longitud último tramo: 9.61 m
Longitud total: 9.61 m

Figure 4.3. *Step 1. Hydropower potential assessment, H estimation. (a) Geovisualization tool used (b) WWTP coordinates, including elevation (c) discharge point coordinates, including elevation (d) distance estimation.*

4.4.2. Technical assessment of hydropower potential (Step 1)

The assessment in this step includes technical criteria only, so, unlike other methodologies, no sites were discarded for economic reasons. Following the procedure described in 4.3.2, a final group of 34 sites out of the 186 WWTPs in the initial sample showed a potential power higher than 100 W. For this group, the generation of electricity was estimated at 340,472 kWh/year. As expected, this value is far from the current generation from CHP, although it could be regarded as complementary (Llácer-Iglesias et al., 2021a, 2021b; Ministry for Ecological Transition & Demographic Challenge, 2021). In the final group of sites, only 1 out of 34 showed potential for CHP, therefore, further implementation of this technology might be limited too. Furthermore, although the initial sample of plants is different, the comparison of this value with the foreseen generation from solar energy (see 4.4.1.1.), indicates that in future actions, hydropower might deserve some attention too.

Fig. 4.4 shows each of the partial outcomes obtained during this process. Some sites were merely discarded because they were not well identified, or their data were not available. Only plants whose effluents are discharged into inland water bodies were considered. Thus, those cases where they are discharged by means of ground infiltration or sea outfalls were discarded too. All the assumptions and estimations made during the process tried to be conservative. Sites showing negative elevation heads probably use pumping to reach the receiving water bodies, but they were just discarded as the analysis of their options was beyond the scope of this study. After a preliminary screening, a minimum H of 1 m was established, not for technical reasons, but considering the possible inaccuracies in the head estimation method.

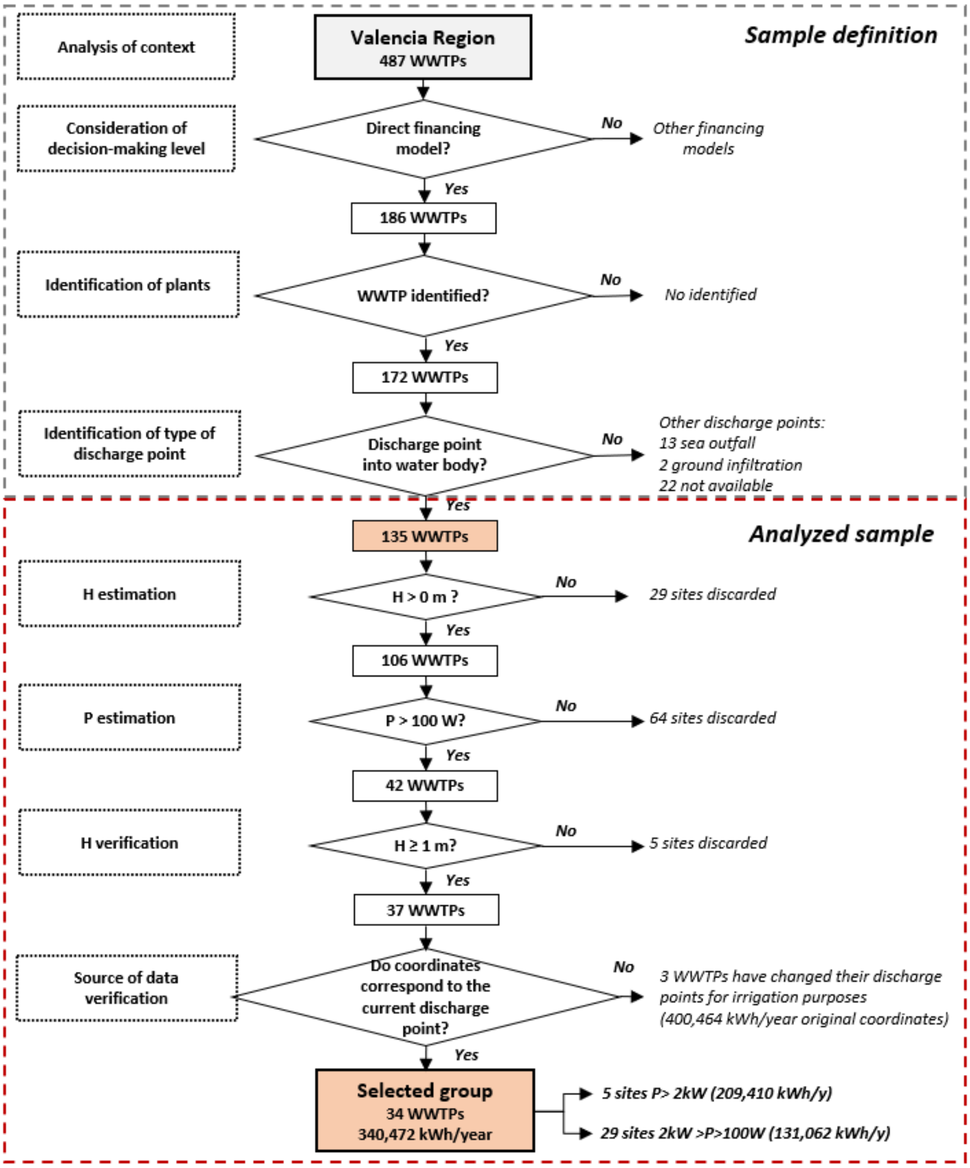


Figure 4.4. *Step 1. Process and outcomes in the determination of the technical hydropower potential for the selected sample*

Finally, as part of the sensitivity analysis conducted in this study (see Section 4.4.4), when different sources of data were used (basin agencies and EPSAR) the comparison highlighted one important finding. The location of some discharge points might be modified, and these modifications could have important effects on the results. On the one hand, in this study, initial screening and calculations based on the basin agency data (discharge points coordinates and volumes), showed 3 additional sites, finally not included in the results. These sites showed the highest potential values, with an additional generation of 400,464 kWh/year, i. e. duplicating the results. However, according to 2021 data, nowadays 100% of the effluent in these plants is used for irrigation purposes (EPSAR, 2022). Therefore, the calculations with their original coordinates would not offer valid results, so the 3 sites were discarded. On the other hand, as described in Section 4.4.4, if modifications of current discharge points at some sites were feasible, the potential could be higher than the given results.

From the results of this technical assessment, two scenarios were considered to apply the sustainability criteria in step 2:

- Scenario (1) considers the cut-off point proposed in this methodology (based on technical feasibility). The group consists of 34 sites with P>100 W, 5 of them with P>2 kW.
- Scenario (2) considers the lowest cut-off point proposed in previous methodologies (based on economic feasibility). The group includes only the 5 plants with P>2 kW.

4.4.3. Global assessment in a sustainability framework (Step 2)

Once the technical assessment was conducted, other criteria were considered to put these results into context. As mentioned, for the case study in this research, a key issue was to align the whole methodology developed in this step, with the PDSEAR guidelines, adapted to the energy focus.

PDSEAR proposes the application of a SAW method for the decision-making processes in the urban wastewater planning in Spain. Therefore, to achieve a full alignment with this instrument, this was the method applied in this study. However, the application of the approach presented here to any other context, should define the most suitable MCDA method to develop in a preliminary stage.

The proposal in these guidelines is focused on the environmental dimension since those criteria are based on compliance with water regulations. After a first classification according to these criteria, it also considers 3–4 factors in each of the other 2 dimensions, economic (including technical aspects) and social (including policy aspects), to establish a prioritization order for actions.

4.4.3.1.Case study criteria definition

Criteria selection

A set of criteria that could be suitable for a case study in the Spanish context was selected as described in Section 4.3.3.2. To gather information for the criteria definition, the questionnaire (Fig. 4.2) was sent to 2 main stakeholders, EPSAR and one of the companies that monitor the technical performance of WWTPs in the region. Both, with several experts in their staff. However, the response was low, and only 4 answers were received (1 from EPSAR, and 3 from the company). Besides, the answers did not show strong preferences, ranking almost all factors as very important or crucial. So, finally they were only used to validate the consistency of the proposal made by the authors according to the literature, the selection factors, and the PDSEAR model. That is, showing no contradictory results or different perspective. To keep this broad perspective, although some criteria or their ranking scales were tailored to this context, when possible, universal indicators were considered. Fig. 4.5 summarizes the outcomes of this step.

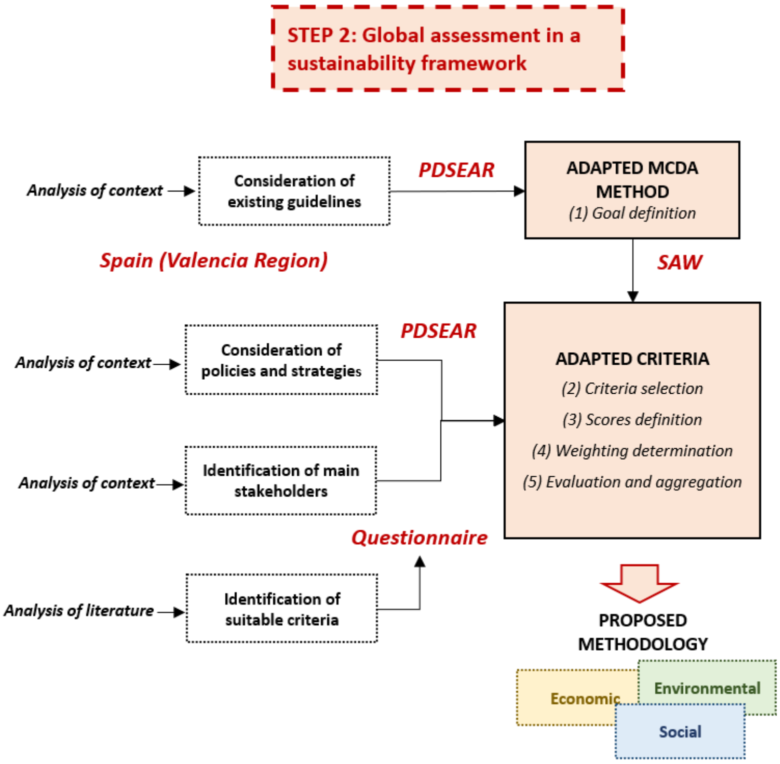


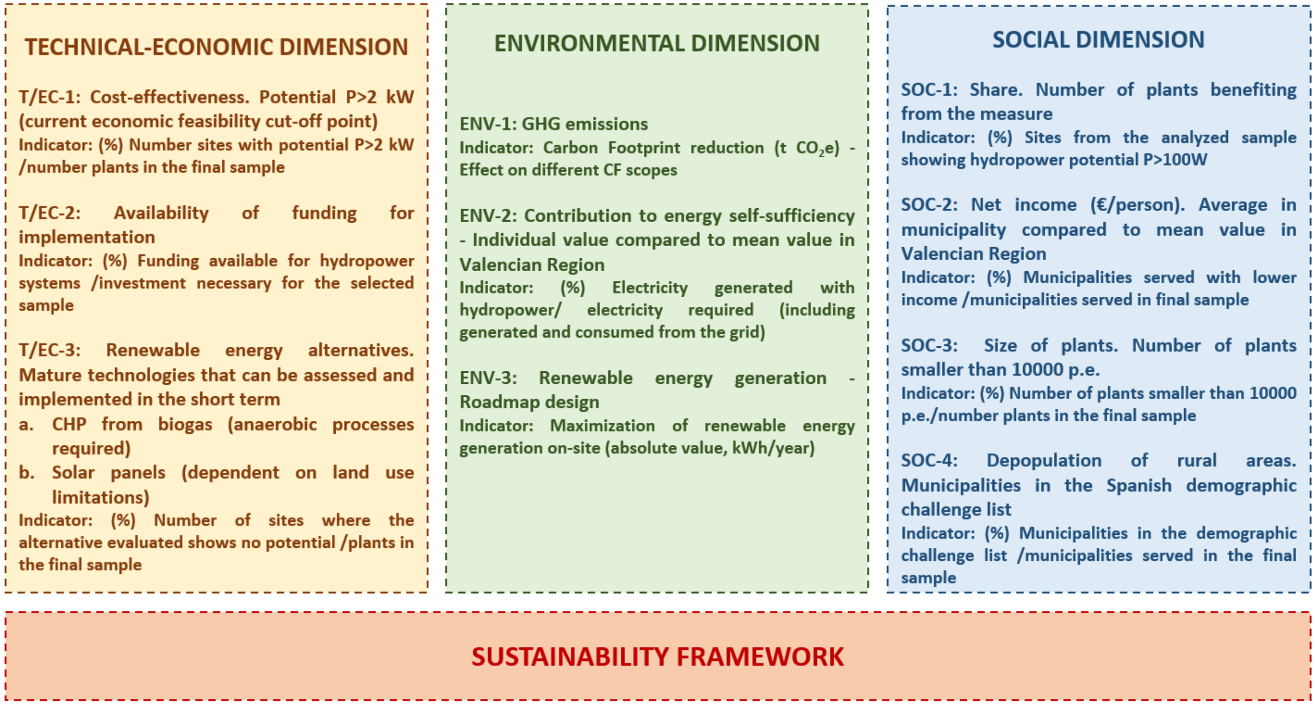
Figure 4.5. *Step 2. Process and outcomes in the determination of the global assessment for the selected sample*

As a result, 10 criteria were proposed, 3 of them related to the economic dimension, 3 to the environmental, and 4 to the social dimension (Fig. 4.6). Some technical considerations were included in the economic dimension, and some policy aspects in the social dimension (Delanka-Pedige et al., 2021; Ministry for Ecological Transition & Demographic Challenge, 2021). All factors were defined in such a way that the higher the indicator, the higher the score, and therefore, the priority. The relative value of each indicator was defined bearing in mind the type of information to provide.

In the economic dimension, the factors were selected according to the main principles in the European Directive such as cost-effectiveness. To assess individual potential, in this methodology, the lower threshold was established according to technical feasibility, as P>100 W (Llácer-Iglesias et al., 2021b). However, all other studies (Bekker et al., 2022; Bousquet et al., 2017; García et al., 2021; Mitrovic et al., 2021; Power et al., 2014; Punys & Jureviˇcius, 2022) applied the threshold for economic feasibility, reported as P>2 kW in the current market conditions. So, this consideration was introduced as an economic factor. In this dimension funding was another factor to consider, and real options to implement ready-in-the-market solutions were also assessed, with a breakdown of every potential technology to ponder.

The selection of the environmental factors was focused on energy-related issues, provided there are no interferences with the quality of the effluent. The three selected factors are somehow related, but each includes several considerations that affect different strategies. The approaches for each indicator are also different (qualitative vs. quantitative, relative vs. absolute value). All of them are already reported by EPSAR, enabling easy monitoring.

Concerning the social dimension, a National Strategy for Demographic Challenge was approved in Spain in 2019 encouraging the introduction of related criteria, so that basic services are provided according to the principles of equity, territorial balance, and demographic stability (Ministry for Ecological Transition & Demographic Challenge, 2019). These guidelines were applied to define suitable indicators.



TECHNICAL-ECONOMIC DIMENSION

T/EC-1: Cost-effectiveness. Potential P>2 kW (current economic feasibility cut-off point)
Indicator: (%) Number sites with potential P>2 kW /number plants in the final sample

T/EC-2: Availability of funding for implementation
Indicator: (%) Funding available for hydropower systems /investment necessary for the selected sample

T/EC-3: Renewable energy alternatives. Mature technologies that can be assessed and implemented in the short term

a. CHP from biogas (anaerobic processes required)
b. Solar panels (dependent on land use limitations)

Indicator: (%) Number of sites where the alternative evaluated shows no potential /plants in the final sample

ENVIRONMENTAL DIMENSION

ENV-1: GHG emissions
Indicator: Carbon Footprint reduction (t CO_2e) - Effect on different CF scopes

ENV-2: Contribution to energy self-sufficiency - Individual value compared to mean value in Valencian Region
Indicator: (%) Electricity generated with hydropower/ electricity required (including generated and consumed from the grid)

ENV-3: Renewable energy generation - Roadmap design
Indicator: Maximization of renewable energy generation on-site (absolute value, kWh/year)

SOCIAL DIMENSION

SOC-1: Share. Number of plants benefiting from the measure
Indicator: (%) Sites from the analyzed sample showing hydropower potential P>100W

SOC-2: Net income (€/person). Average in municipality compared to mean value in Valencian Region
Indicator: (%) Municipalities served with lower income /municipalities served in final sample

SOC-3: Size of plants. Number of plants smaller than 10000 p.e.
Indicator: (%) Number of plants smaller than 10000 p.e./number plants in the final sample

SOC-4: Depopulation of rural areas. Municipalities in the Spanish demographic challenge list
Indicator: (%) Municipalities in the demographic challenge list /municipalities served in the final sample

SUSTAINABILITY FRAMEWORK

Figure 4.6. *Proposed sustainability criteria for the case study*

Criteria scores definition

Again, the definition of the scale of prioritization was established according to the PDSEAR model. In particular, the percentile approach, which makes normalization not necessary. This approach is based on the consideration of a target or average value, and analyzes the percentage of items in the sample, that are above or below that threshold. As a three-level scale is applied, an accumulative 33.33% is considered at each level. Therefore, this approach is appropriate to evaluate the group as a whole, which was one of the requirements in the design of the methodology. Finally, some distinctive features of the Valencia Region were also added.

Figs. 4.7, 4.8 and 4.9 include the whole evaluation process for each dimension, including for each criterion a summary of its definition and related indicator, its ranking scale, and the corresponding data and scores for scenarios 1 and 2. The higher the priority, the higher the score. So, priority 1 corresponds to the highest priority, and the corresponding score is 3, whereas priority 3 is the lowest, so the score assigned is 1.

Weighting determination

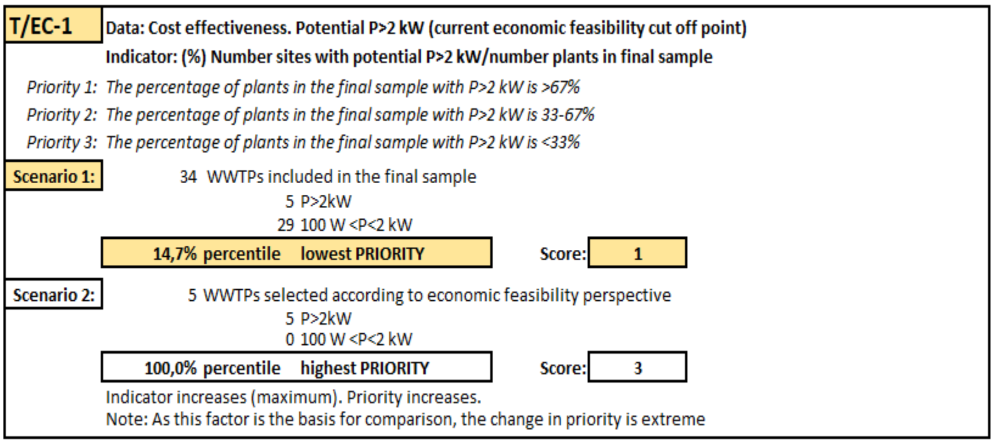
According to the responses to the questionnaires and consistent with the literature, it was assigned the same weighting to every dimension (33.33%), with identical distribution for each criterion within a dimension. This decision was also consistent with the PDSEAR approach, which also considers an equal distribution of weights too. The effects of potential modifications on the results can be seen in Section 4.4.4, as part of the sensitivity analysis.

4.4.3.2. Case study criteria application

Evaluation and aggregation

The proposed criteria were applied to the group of sites selected in Step 1, considering the 2 scenarios indicated in 4.4.2 (see Figs. 4.7, 4.8, and 4.9). Comparing the rankings for both scenarios, in most environmental (Fig. 4.8), and social (Fig. 4.9) indicators, the value decreases in scenario 2, although it does not always imply a lower priority. This comparison shows the effects on the results depending on the perspective applied. The aggregated results are shown in Fig. 4.10.

The AV obtained with the proposed criteria are almost identical in both scenarios. However, the partial scores for each dimension clearly illustrate the differences between the two approaches. In any case, the priority results are in the intermediate range, which again would imply that hydropower might be an interesting option to explore, regardless of the initial approach. The sensitivity analysis described in the next section also confirmed these observations.



T/EC-1 **Data: Cost effectiveness. Potential P>2 kW (current economic feasibility cut off point)**

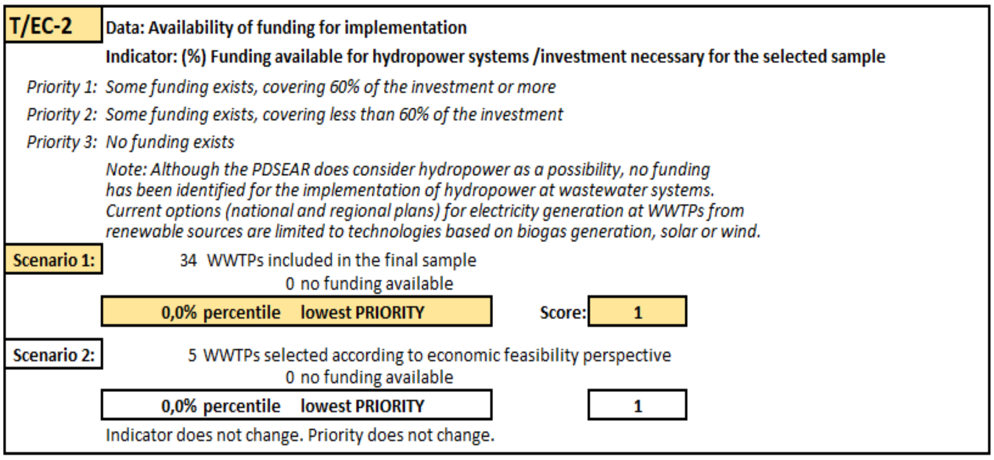
Indicator: (%) Number sites with potential P>2 kW/number plants in final sample

Priority 1: The percentage of plants in the final sample with P>2 kW is >67%
Priority 2: The percentage of plants in the final sample with P>2 kW is 33-67%
Priority 3: The percentage of plants in the final sample with P>2 kW is <33%

Scenario 1: 34 WWTPs included in the final sample
5 P>2kW
29 100 W <P<2 kW
14,7% percentile **lowest PRIORITY** **Score:** 1

Scenario 2: 5 WWTPs selected according to economic feasibility perspective
5 P>2kW
0 100 W <P<2 kW
100,0% percentile **highest PRIORITY** **Score:** 3

Indicator increases (maximum). Priority increases.
Note: As this factor is the basis for comparison, the change in priority is extreme



T/EC-2 **Data: Availability of funding for implementation**

Indicator: (%) Funding available for hydropower systems /investment necessary for the selected sample

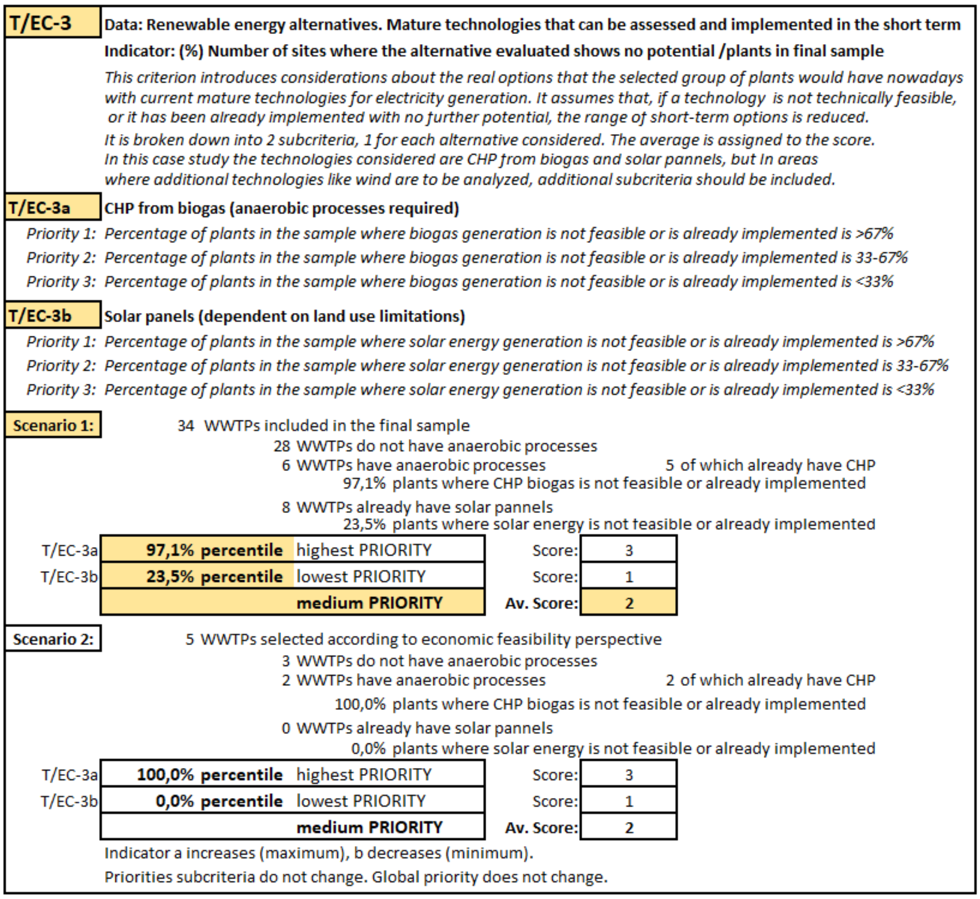
Priority 1: Some funding exists, covering 60% of the investment or more
Priority 2: Some funding exists, covering less than 60% of the investment
Priority 3: No funding exists

Note: Although the PDSEAR does consider hydropower as a possibility, no funding has been identified for the implementation of hydropower at wastewater systems. Current options (national and regional plans) for electricity generation at WWTPs from renewable sources are limited to technologies based on biogas generation, solar or wind.

Scenario 1: 34 WWTPs included in the final sample
0 no funding available
0,0% percentile **lowest PRIORITY** **Score:** 1

Scenario 2: 5 WWTPs selected according to economic feasibility perspective
0 no funding available
0,0% percentile **lowest PRIORITY** 1

Indicator does not change. Priority does not change.



T/EC-3 **Data: Renewable energy alternatives. Mature technologies that can be assessed and implemented in the short term**

Indicator: (%) Number of sites where the alternative evaluated shows no potential /plants in final sample

This criterion introduces considerations about the real options that the selected group of plants would have nowadays with current mature technologies for electricity generation. It assumes that, if a technology is not technically feasible, or it has been already implemented with no further potential, the range of short-term options is reduced.
It is broken down into 2 subcriteria, 1 for each alternative considered. The average is assigned to the score.
In this case study the technologies considered are CHP from biogas and solar pannels, but In areas where additional technologies like wind are to be analyzed, additional subcriteria should be included.

T/EC-3a **CHP from biogas (anaerobic processes required)**

Priority 1: Percentage of plants in the sample where biogas generation is not feasible or is already implemented is >67%
Priority 2: Percentage of plants in the sample where biogas generation is not feasible or is already implemented is 33-67%
Priority 3: Percentage of plants in the sample where biogas generation is not feasible or is already implemented is <33%

T/EC-3b **Solar panels (dependent on land use limitations)**

Priority 1: Percentage of plants in the sample where solar energy generation is not feasible or is already implemented is >67%
Priority 2: Percentage of plants in the sample where solar energy generation is not feasible or is already implemented is 33-67%
Priority 3: Percentage of plants in the sample where solar energy generation is not feasible or is already implemented is <33%

Scenario 1:

34 WWTPs included in the final sample
28 WWTPs do not have anaerobic processes
6 WWTPs have anaerobic processes — 5 of which already have CHP
97,1% plants where CHP biogas is not feasible or already implemented
8 WWTPs already have solar pannels
23,5% plants where solar energy is not feasible or already implemented

T/EC-3a	**97,1% percentile**	highest PRIORITY	Score:	3
T/EC-3b	**23,5% percentile**	lowest PRIORITY	Score:	1
		medium PRIORITY	**Av. Score:**	2

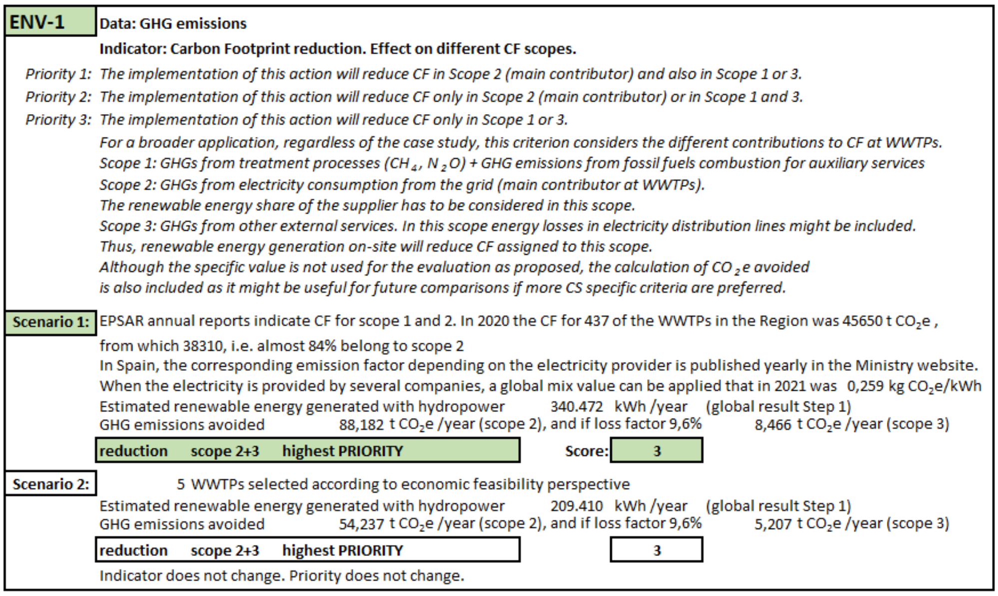
Scenario 2:

5 WWTPs selected according to economic feasibility perspective
3 WWTPs do not have anaerobic processes
2 WWTPs have anaerobic processes — 2 of which already have CHP
100,0% plants where CHP biogas is not feasible or already implemented
0 WWTPs already have solar pannels
0,0% plants where solar energy is not feasible or already implemented

T/EC-3a	**100,0% percentile**	highest PRIORITY	Score:	3
T/EC-3b	**0,0% percentile**	lowest PRIORITY	Score:	1
		medium PRIORITY	**Av. Score:**	2

Indicator a increases (maximum), b decreases (minimum).
Priorities subcriteria do not change. Global priority does not change.

Figure 4.7. *Technical and Economic dimension. Evaluation criteria, ranking scales, and scores.*



ENV-1 **Data: GHG emissions**

Indicator: Carbon Footprint reduction. Effect on different CF scopes.

Priority 1: The implementation of this action will reduce CF in Scope 2 (main contributor) and also in Scope 1 or 3.
Priority 2: The implementation of this action will reduce CF only in Scope 2 (main contributor) or in Scope 1 and 3.
Priority 3: The implementation of this action will reduce CF only in Scope 1 or 3.
For a broader application, regardless of the case study, this criterion considers the different contributions to CF at WWTPs.
Scope 1: GHGs from treatment processes (CH_4, N_2O) + GHG emissions from fossil fuels combustion for auxiliary services
Scope 2: GHGs from electricity consumption from the grid (main contributor at WWTPs).
The renewable energy share of the supplier has to be considered in this scope.
Scope 3: GHGs from other external services. In this scope energy losses in electricity distribution lines might be included.
Thus, renewable energy generation on-site will reduce CF assigned to this scope.
Although the specific value is not used for the evaluation as proposed, the calculation of CO_2e avoided
is also included as it might be useful for future comparisons if more CS specific criteria are preferred.

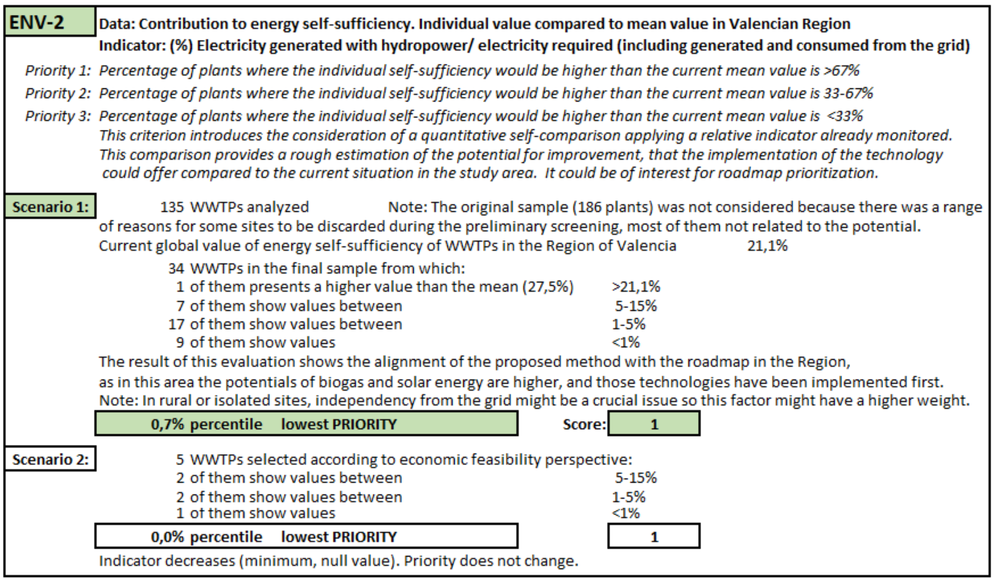
Scenario 1: EPSAR annual reports indicate CF for scope 1 and 2. In 2020 the CF for 437 of the WWTPs in the Region was 45650 t CO_2e ,
from which 38310, i.e. almost 84% belong to scope 2
In Spain, the corresponding emission factor depending on the electricity provider is published yearly in the Ministry website.
When the electricity is provided by several companies, a global mix value can be applied that in 2021 was 0,259 kg CO_2e/kWh
Estimated renewable energy generated with hydropower 340.472 kWh /year (global result Step 1)
GHG emissions avoided 88,182 t CO_2e /year (scope 2), and if loss factor 9,6% 8,466 t CO_2e /year (scope 3)

reduction scope 2+3 highest PRIORITY **Score: 3**

Scenario 2: 5 WWTPs selected according to economic feasibility perspective
Estimated renewable energy generated with hydropower 209.410 kWh /year (global result Step 1)
GHG emissions avoided 54,237 t CO_2e /year (scope 2), and if loss factor 9,6% 5,207 t CO_2e /year (scope 3)

reduction scope 2+3 highest PRIORITY **3**

Indicator does not change. Priority does not change.



ENV-2 **Data: Contribution to energy self-sufficiency. Individual value compared to mean value in Valencian Region**
Indicator: (%) Electricity generated with hydropower/ electricity required (including generated and consumed from the grid)

Priority 1: Percentage of plants where the individual self-sufficiency would be higher than the current mean value is >67%
Priority 2: Percentage of plants where the individual self-sufficiency would be higher than the current mean value is 33-67%
Priority 3: Percentage of plants where the individual self-sufficiency would be higher than the current mean value is <33%
This criterion introduces the consideration of a quantitative self-comparison applying a relative indicator already monitored.
This comparison provides a rough estimation of the potential for improvement, that the implementation of the technology could offer compared to the current situation in the study area. It could be of interest for roadmap prioritization.

Scenario 1: 135 WWTPs analyzed Note: The original sample (186 plants) was not considered because there was a range
of reasons for some sites to be discarded during the preliminary screening, most of them not related to the potential.
Current global value of energy self-sufficiency of WWTPs in the Region of Valencia 21,1%

34	WWTPs in the final sample from which:	
1	of them presents a higher value than the mean (27,5%)	>21,1%
7	of them show values between	5-15%
17	of them show values between	1-5%
9	of them show values	<1%

The result of this evaluation shows the alignment of the proposed method with the roadmap in the Region,
as in this area the potentials of biogas and solar energy are higher, and those technologies have been implemented first.
Note: In rural or isolated sites, independency from the grid might be a crucial issue so this factor might have a higher weight.

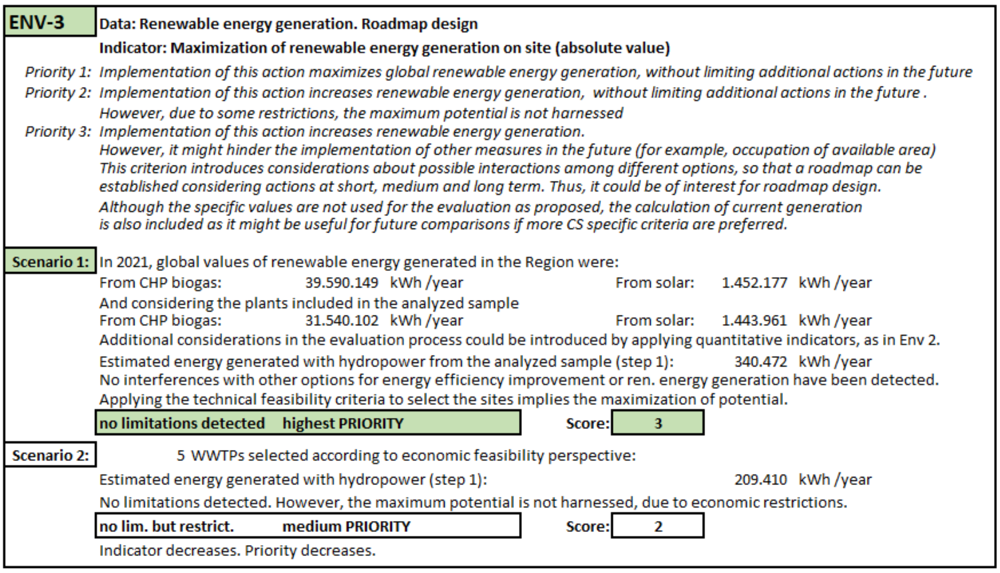
0,7% percentile lowest PRIORITY **Score: 1**

Scenario 2:

5	WWTPs selected according to economic feasibility perspective:	
2	of them show values between	5-15%
2	of them show values between	1-5%
1	of them show values	<1%

0,0% percentile lowest PRIORITY **1**

Indicator decreases (minimum, null value). Priority does not change.



ENV-3 **Data: Renewable energy generation. Roadmap design**

Indicator: Maximization of renewable energy generation on site (absolute value)

Priority 1: *Implementation of this action maximizes global renewable energy generation, without limiting additional actions in the future*
Priority 2: *Implementation of this action increases renewable energy generation, without limiting additional actions in the future .*
However, due to some restrictions, the maximum potential is not harnessed
Priority 3: *Implementation of this action increases renewable energy generation.*
However, it might hinder the implementation of other measures in the future (for example, occupation of available area)

This criterion introduces considerations about possible interactions among different options, so that a roadmap can be established considering actions at short, medium and long term. Thus, it could be of interest for roadmap design.

Although the specific values are not used for the evaluation as proposed, the calculation of current generation is also included as it might be useful for future comparisons if more CS specific criteria are preferred.

Scenario 1: In 2021, global values of renewable energy generated in the Region were:

From CHP biogas:	39.590.149	kWh /year	From solar:	1.452.177	kWh /year

And considering the plants included in the analyzed sample

From CHP biogas:	31.540.102	kWh /year	From solar:	1.443.961	kWh /year

Additional considerations in the evaluation process could be introduced by applying quantitative indicators, as in Env 2.

Estimated energy generated with hydropower from the analyzed sample (step 1): 340.472 kWh /year

No interferences with other options for energy efficiency improvement or ren. energy generation have been detected.

Applying the technical feasibility criteria to select the sites implies the maximization of potential.

no limitations detected **highest PRIORITY** **Score:** **3**

Scenario 2: 5 WWTPs selected according to economic feasibility perspective:

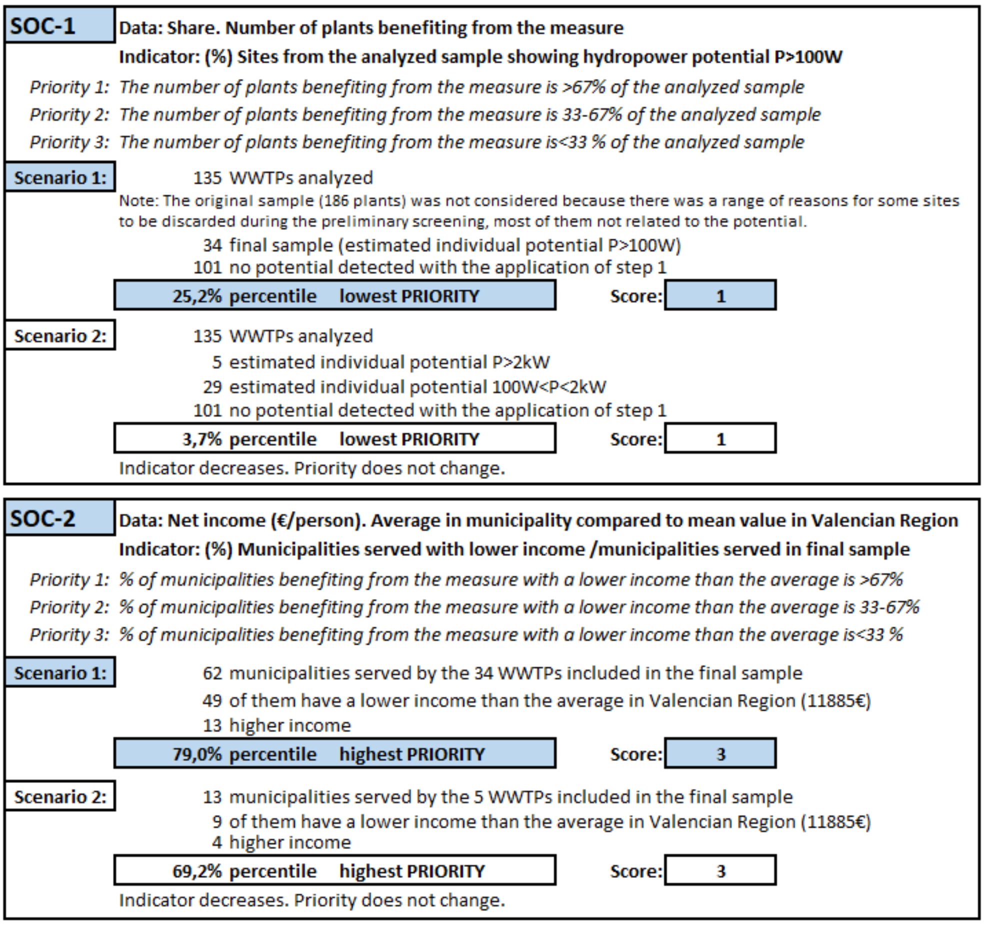
Estimated energy generated with hydropower (step 1): 209.410 kWh /year

No limitations detected. However, the maximum potential is not harnessed, due to economic restrictions.

no lim. but restrict. **medium PRIORITY** **Score:** **2**

Indicator decreases. Priority decreases.

Figure 4.8. *Environmental dimension. Evaluation criteria, ranking scales, and scores.*



SOC-1 **Data: Share. Number of plants benefiting from the measure**

Indicator: (%) Sites from the analyzed sample showing hydropower potential P>100W

Priority 1: The number of plants benefiting from the measure is >67% of the analyzed sample

Priority 2: The number of plants benefiting from the measure is 33-67% of the analyzed sample

Priority 3: The number of plants benefiting from the measure is<33 % of the analyzed sample

Scenario 1:

135 WWTPs analyzed

Note: The original sample (186 plants) was not considered because there was a range of reasons for some sites to be discarded during the preliminary screening, most of them not related to the potential.

34 final sample (estimated individual potential P>100W)

101 no potential detected with the application of step 1

25,2% percentile lowest PRIORITY **Score: 1**

Scenario 2:

135 WWTPs analyzed

5 estimated individual potential P>2kW

29 estimated individual potential 100W<P<2kW

101 no potential detected with the application of step 1

3,7% percentile lowest PRIORITY **Score: 1**

Indicator decreases. Priority does not change.

SOC-2 **Data: Net income (€/person). Average in municipality compared to mean value in Valencian Region**

Indicator: (%) Municipalities served with lower income /municipalities served in final sample

Priority 1: % of municipalities benefiting from the measure with a lower income than the average is >67%

Priority 2: % of municipalities benefiting from the measure with a lower income than the average is 33-67%

Priority 3: % of municipalities benefiting from the measure with a lower income than the average is<33 %

Scenario 1:

62 municipalities served by the 34 WWTPs included in the final sample

49 of them have a lower income than the average in Valencian Region (11885€)

13 higher income

79,0% percentile highest PRIORITY **Score: 3**

Scenario 2:

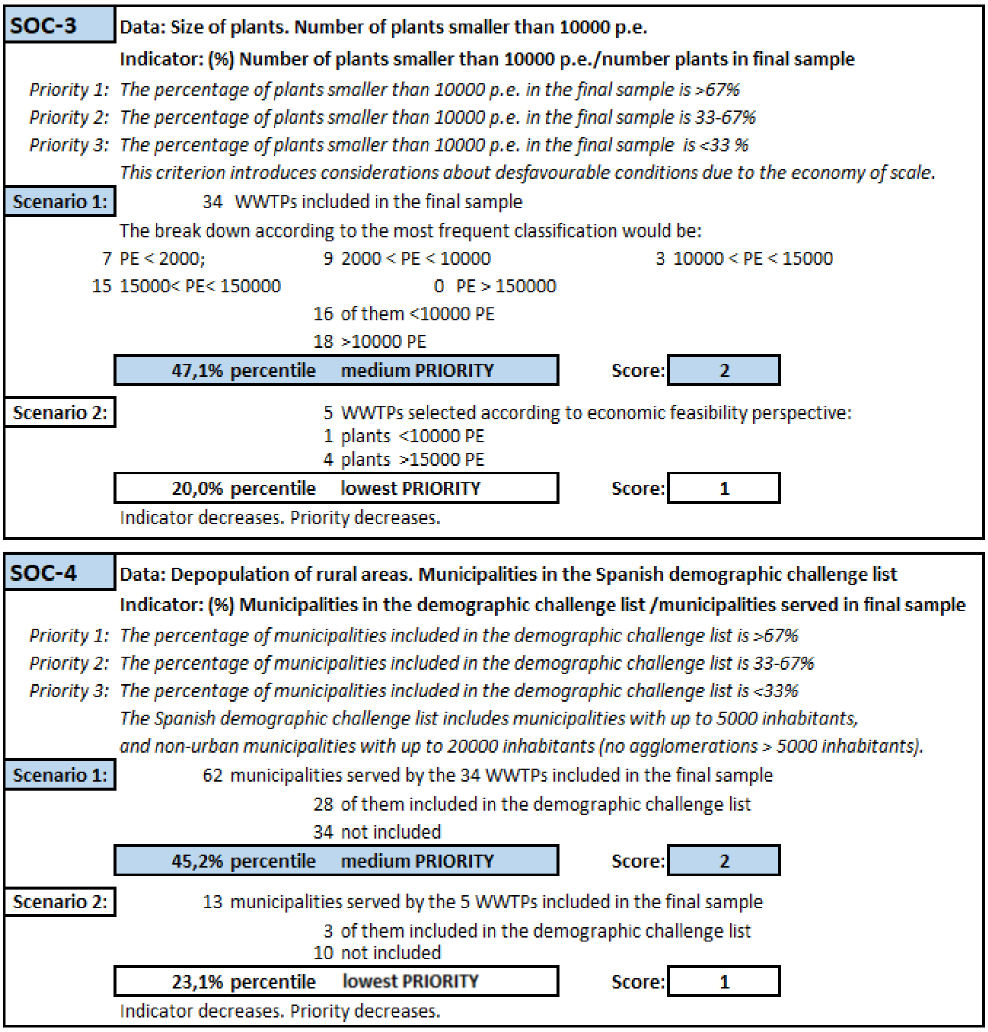
13 municipalities served by the 5 WWTPs included in the final sample

9 of them have a lower income than the average in Valencian Region (11885€)

4 higher income

69,2% percentile highest PRIORITY **Score: 3**

Indicator decreases. Priority does not change.



SOC-3 **Data: Size of plants. Number of plants smaller than 10000 p.e.**

Indicator: (%) Number of plants smaller than 10000 p.e./number plants in final sample

Priority 1: The percentage of plants smaller than 10000 p.e. in the final sample is >67%
Priority 2: The percentage of plants smaller than 10000 p.e. in the final sample is 33-67%
Priority 3: The percentage of plants smaller than 10000 p.e. in the final sample is <33 %
This criterion introduces considerations about desfavourable conditions due to the economy of scale.

Scenario 1: 34 WWTPs included in the final sample

The break down according to the most frequent classification would be:
7 PE < 2000; 9 2000 < PE < 10000 3 10000 < PE < 15000
15 15000< PE< 150000 0 PE > 150000
16 of them <10000 PE
18 >10000 PE

47,1% percentile medium PRIORITY **Score: 2**

Scenario 2: 5 WWTPs selected according to economic feasibility perspective:
1 plants <10000 PE
4 plants >15000 PE

20,0% percentile lowest PRIORITY **Score: 1**

Indicator decreases. Priority decreases.

SOC-4 **Data: Depopulation of rural areas. Municipalities in the Spanish demographic challenge list**

Indicator: (%) Municipalities in the demographic challenge list /municipalities served in final sample

Priority 1: The percentage of municipalities included in the demographic challenge list is >67%
Priority 2: The percentage of municipalities included in the demographic challenge list is 33-67%
Priority 3: The percentage of municipalities included in the demographic challenge list is <33%
The Spanish demographic challenge list includes municipalities with up to 5000 inhabitants,
and non-urban municipalities with up to 20000 inhabitants (no agglomerations > 5000 inhabitants).

Scenario 1: 62 municipalities served by the 34 WWTPs included in the final sample
28 of them included in the demographic challenge list
34 not included

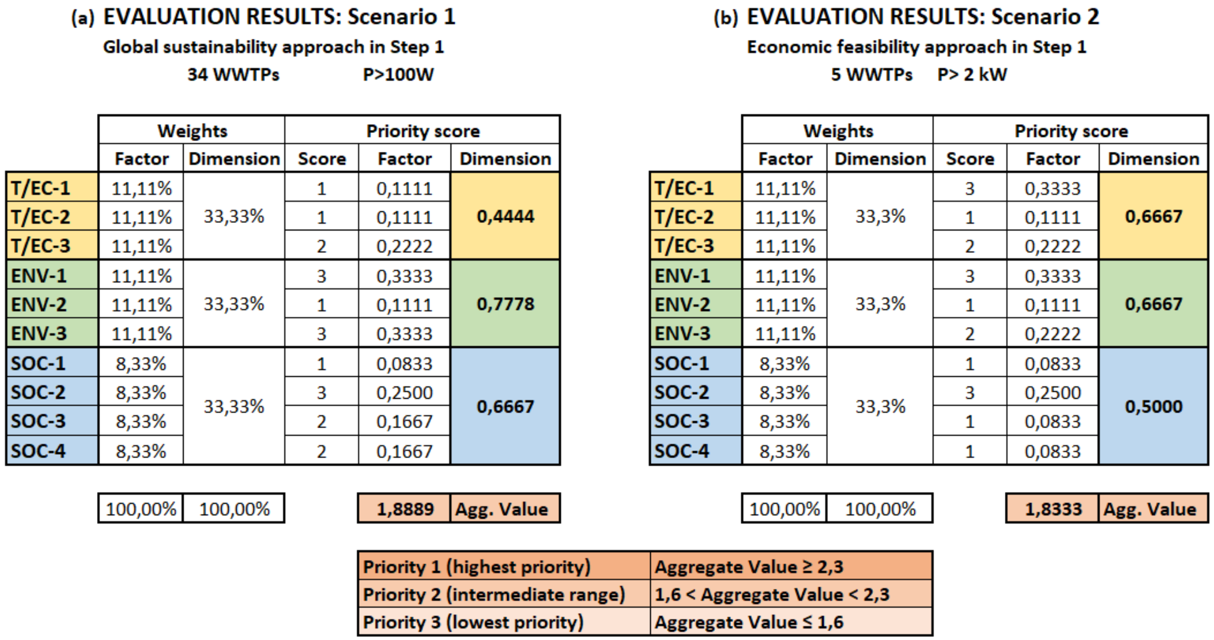
45,2% percentile medium PRIORITY **Score: 2**

Scenario 2: 13 municipalities served by the 5 WWTPs included in the final sample
3 of them included in the demographic challenge list
10 not included

23,1% percentile lowest PRIORITY **Score: 1**

Indicator decreases. Priority decreases.

Figure 4.9. *Social dimension. Evaluation criteria, ranking scales, and scores.*



(a) EVALUATION RESULTS: Scenario 1

Global sustainability approach in Step 1

34 WWTPs P>100W

	Weights		**Priority score**		
	Factor	**Dimension**	**Score**	**Factor**	**Dimension**
T/EC-1	11,11%	33,33%	1	0,1111	**0,4444**
T/EC-2	11,11%		1	0,1111	
T/EC-3	11,11%		2	0,2222	
ENV-1	11,11%	33,33%	3	0,3333	**0,7778**
ENV-2	11,11%		1	0,1111	
ENV-3	11,11%		3	0,3333	
SOC-1	8,33%	33,33%	1	0,0833	**0,6667**
SOC-2	8,33%		3	0,2500	
SOC-3	8,33%		2	0,1667	
SOC-4	8,33%		2	0,1667	
	100,00%	100,00%		**1,8889**	**Agg. Value**

(b) EVALUATION RESULTS: Scenario 2

Economic feasibility approach in Step 1

5 WWTPs P> 2 kW

	Weights		**Priority score**		
	Factor	**Dimension**	**Score**	**Factor**	**Dimension**
T/EC-1	11,11%	33,3%	3	0,3333	**0,6667**
T/EC-2	11,11%		1	0,1111	
T/EC-3	11,11%		2	0,2222	
ENV-1	11,11%	33,3%	3	0,3333	**0,6667**
ENV-2	11,11%		1	0,1111	
ENV-3	11,11%		2	0,2222	
SOC-1	8,33%	33,3%	1	0,0833	**0,5000**
SOC-2	8,33%		3	0,2500	
SOC-3	8,33%		1	0,0833	
SOC-4	8,33%		1	0,0833	
	100,00%	100,00%		**1,8333**	**Agg. Value**

Priority 1 (highest priority)	**Aggregate Value ≥ 2,3**
Priority 2 (intermediate range)	**1,6 < Aggregate Value < 2,3**
Priority 3 (lowest priority)	**Aggregate Value ≤ 1,6**

Figure 4.10. *Evaluation results, aggregate values (AV). (a) Scenario 1: Global sustainability approach in Step 1 (34 WWTPs with P>100 W). (b) Scenario 2: Economic feasibility approach in Step 1 (5 WWTPs with P>2kW).*

4.4.4. Sensitivity analysis

The final stage of this study evaluated the effects on the results, when some of the considerations of the applied methodology were changed.

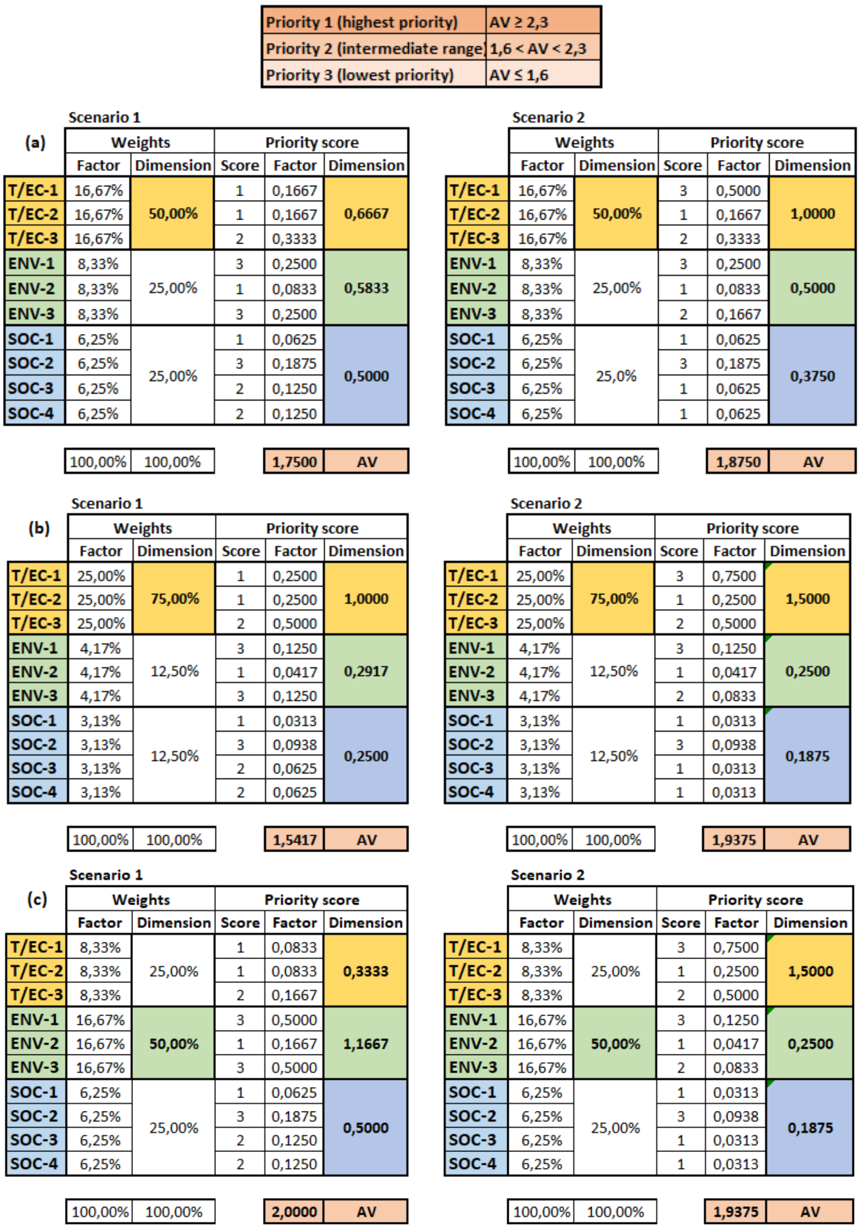
Step 1

Effects of variations of data, depending on the year of data, the source of data, and the location of the discharge point were evaluated. The variation of year and source of data did not result in significant quantitative changes. However, as mentioned in 4.4.2, the variation of sources enabled the identification of recent modifications of some discharge points, due to the increasing use of reclaimed water for irrigation. Thus, 3 potential sites, that initially showed the highest potential, were finally discarded. Nevertheless, this finding reinforced the idea that, maybe, some other discharge points could also be modified to maximize the power. Possible modifications, that would result in a higher potential, were detected in 8 of the 34 plants, 2 of them, crossing the 2-kW threshold. This would result in 7 out of 34 plants, above this threshold, and an estimated generation of 453,335 kWh, i.e. a 33% increment in the result. Applying the same assumptions to the discarded plants, 5 additional sites could be added to the final group. Therefore, the resulting group would consist of 39 sites (Scenario 1), with 7 of them with P > 2 kW (Scenario 2), increasing the potential generation by 37.5% (to 468,434 kWh/year).

Step 2

According to the literature, this process is very important, since the choices made might affect the results in real life applications (Vlachokostas et al., 2021). So effects of variations in the distribution of weights per dimension and variations in rankings due to changes in the external context were evaluated. Hence, the evaluation was repeated giving prevalence to each dimension above the other two, with the two following distributions: 50–25–25% and 75–12.5–12.5%. These distributions were based on the real options in the applied case study, as the current policies and strategies in social and environmental aspects, both, from the Spanish and the Valencian institutions, limit remarkably the range of possibilities (Generalitat Valenciana, 2022b; Ministry for Ecological Transition & Demographic Challenge, 2019, 2021). Fig. 4.11 shows the results of the effects of variations in the distribution of weights per dimension.

As shown in Fig. 4.11, regardless of the distribution, the results remain in the intermediate priority in most combinations. This is consistent with the fact that solar energy is also a mature technology, with available funding and still high potential in this region. Only the combination in b (75% technical and economic - 12.5% environmental - 12.5% social) reaches the lowest priority for Scenario 1, which precisely reflects the current framework, illustrating the motivation of this research. Therefore, these results reinforce the rationale of this study, that hydropower might deserve some more attention. However, neither the highest priority is reached unless the context changes.



Priority 1 (highest priority)	AV ≥ 2,3
Priority 2 (intermediate range)	1,6 < AV < 2,3
Priority 3 (lowest priority)	AV ≤ 1,6

(a)

Scenario 1

	Weights		Priority score		
	Factor	Dimension	Score	Factor	Dimension
T/EC-1	16,67%	50,00%	1	0,1667	0,6667
T/EC-2	16,67%		1	0,1667	
T/EC-3	16,67%		2	0,3333	
ENV-1	8,33%	25,00%	3	0,2500	0,5833
ENV-2	8,33%		1	0,0833	
ENV-3	8,33%		3	0,2500	
SOC-1	6,25%	25,00%	1	0,0625	0,5000
SOC-2	6,25%		3	0,1875	
SOC-3	6,25%		2	0,1250	
SOC-4	6,25%		2	0,1250	
	100,00%	100,00%		1,7500	AV

Scenario 2

	Weights		Priority score		
	Factor	Dimension	Score	Factor	Dimension
T/EC-1	16,67%	50,00%	3	0,5000	1,0000
T/EC-2	16,67%		1	0,1667	
T/EC-3	16,67%		2	0,3333	
ENV-1	8,33%	25,00%	3	0,2500	0,5000
ENV-2	8,33%		1	0,0833	
ENV-3	8,33%		2	0,1667	
SOC-1	6,25%	25,0%	1	0,0625	0,3750
SOC-2	6,25%		3	0,1875	
SOC-3	6,25%		1	0,0625	
SOC-4	6,25%		1	0,0625	
	100,00%	100,00%		1,8750	AV

(b)

Scenario 1

	Weights		Priority score		
	Factor	Dimension	Score	Factor	Dimension
T/EC-1	25,00%	75,00%	1	0,2500	1,0000
T/EC-2	25,00%		1	0,2500	
T/EC-3	25,00%		2	0,5000	
ENV-1	4,17%	12,50%	3	0,1250	0,2917
ENV-2	4,17%		1	0,0417	
ENV-3	4,17%		3	0,1250	
SOC-1	3,13%	12,50%	1	0,0313	0,2500
SOC-2	3,13%		3	0,0938	
SOC-3	3,13%		2	0,0625	
SOC-4	3,13%		2	0,0625	
	100,00%	100,00%		1,5417	AV

Scenario 2

	Weights		Priority score		
	Factor	Dimension	Score	Factor	Dimension
T/EC-1	25,00%	75,00%	3	0,7500	1,5000
T/EC-2	25,00%		1	0,2500	
T/EC-3	25,00%		2	0,5000	
ENV-1	4,17%	12,50%	3	0,1250	0,2500
ENV-2	4,17%		1	0,0417	
ENV-3	4,17%		2	0,0833	
SOC-1	3,13%	12,50%	1	0,0313	0,1875
SOC-2	3,13%		3	0,0938	
SOC-3	3,13%		1	0,0313	
SOC-4	3,13%		1	0,0313	
	100,00%	100,00%		1,9375	AV

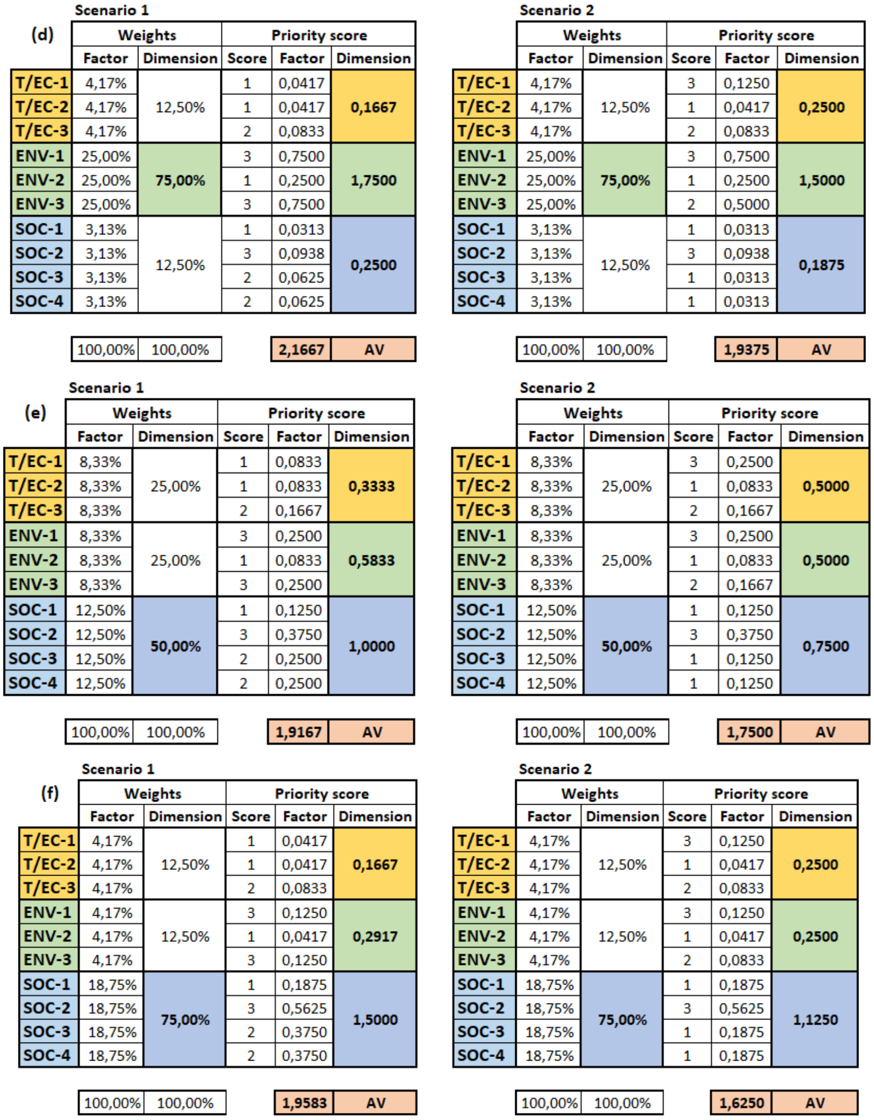
(c)

Scenario 1

	Weights		Priority score		
	Factor	Dimension	Score	Factor	Dimension
T/EC-1	8,33%	25,00%	1	0,0833	0,3333
T/EC-2	8,33%		1	0,0833	
T/EC-3	8,33%		2	0,1667	
ENV-1	16,67%	50,00%	3	0,5000	1,1667
ENV-2	16,67%		1	0,1667	
ENV-3	16,67%		3	0,5000	
SOC-1	6,25%	25,00%	1	0,0625	0,5000
SOC-2	6,25%		3	0,1875	
SOC-3	6,25%		2	0,1250	
SOC-4	6,25%		2	0,1250	
	100,00%	100,00%		2,0000	AV

Scenario 2

	Weights		Priority score		
	Factor	Dimension	Score	Factor	Dimension
T/EC-1	8,33%	25,00%	3	0,7500	1,5000
T/EC-2	8,33%		1	0,2500	
T/EC-3	8,33%		2	0,5000	
ENV-1	16,67%	50,00%	3	0,1250	0,2500
ENV-2	16,67%		1	0,0417	
ENV-3	16,67%		2	0,0833	
SOC-1	6,25%	25,00%	1	0,0313	0,1875
SOC-2	6,25%		3	0,0938	
SOC-3	6,25%		1	0,0313	
SOC-4	6,25%		1	0,0313	
	100,00%	100,00%		1,9375	AV



(d) Scenario 1

	Weights		Priority score		
	Factor	Dimension	Score	Factor	Dimension
T/EC-1	4,17%	12,50%	1	0,0417	0,1667
T/EC-2	4,17%		1	0,0417	
T/EC-3	4,17%		2	0,0833	
ENV-1	25,00%	75,00%	3	0,7500	1,7500
ENV-2	25,00%		1	0,2500	
ENV-3	25,00%		3	0,7500	
SOC-1	3,13%	12,50%	1	0,0313	0,2500
SOC-2	3,13%		3	0,0938	
SOC-3	3,13%		2	0,0625	
SOC-4	3,13%		2	0,0625	
	100,00%	100,00%		2,1667	AV

(d) Scenario 2

	Weights		Priority score		
	Factor	Dimension	Score	Factor	Dimension
T/EC-1	4,17%	12,50%	3	0,1250	0,2500
T/EC-2	4,17%		1	0,0417	
T/EC-3	4,17%		2	0,0833	
ENV-1	25,00%	75,00%	3	0,7500	1,5000
ENV-2	25,00%		1	0,2500	
ENV-3	25,00%		2	0,5000	
SOC-1	3,13%	12,50%	1	0,0313	0,1875
SOC-2	3,13%		3	0,0938	
SOC-3	3,13%		1	0,0313	
SOC-4	3,13%		1	0,0313	
	100,00%	100,00%		1,9375	AV

(e) Scenario 1

	Weights		Priority score		
	Factor	Dimension	Score	Factor	Dimension
T/EC-1	8,33%	25,00%	1	0,0833	0,3333
T/EC-2	8,33%		1	0,0833	
T/EC-3	8,33%		2	0,1667	
ENV-1	8,33%	25,00%	3	0,2500	0,5833
ENV-2	8,33%		1	0,0833	
ENV-3	8,33%		3	0,2500	
SOC-1	12,50%	50,00%	1	0,1250	1,0000
SOC-2	12,50%		3	0,3750	
SOC-3	12,50%		2	0,2500	
SOC-4	12,50%		2	0,2500	
	100,00%	100,00%		1,9167	AV

(e) Scenario 2

	Weights		Priority score		
	Factor	Dimension	Score	Factor	Dimension
T/EC-1	8,33%	25,00%	3	0,2500	0,5000
T/EC-2	8,33%		1	0,0833	
T/EC-3	8,33%		2	0,1667	
ENV-1	8,33%	25,00%	3	0,2500	0,5000
ENV-2	8,33%		1	0,0833	
ENV-3	8,33%		2	0,1667	
SOC-1	12,50%	50,00%	1	0,1250	0,7500
SOC-2	12,50%		3	0,3750	
SOC-3	12,50%		1	0,1250	
SOC-4	12,50%		1	0,1250	
	100,00%	100,00%		1,7500	AV

(f) Scenario 1

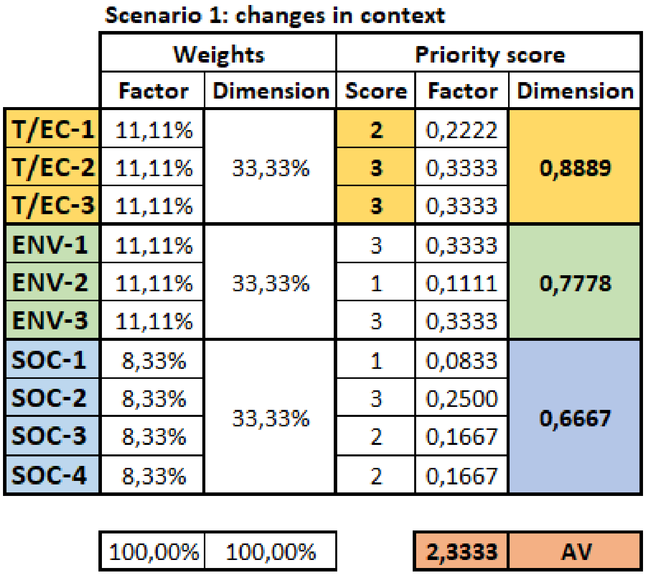
	Weights		Priority score		
	Factor	Dimension	Score	Factor	Dimension
T/EC-1	4,17%	12,50%	1	0,0417	0,1667
T/EC-2	4,17%		1	0,0417	
T/EC-3	4,17%		2	0,0833	
ENV-1	4,17%	12,50%	3	0,1250	0,2917
ENV-2	4,17%		1	0,0417	
ENV-3	4,17%		3	0,1250	
SOC-1	18,75%	75,00%	1	0,1875	1,5000
SOC-2	18,75%		3	0,5625	
SOC-3	18,75%		2	0,3750	
SOC-4	18,75%		2	0,3750	
	100,00%	100,00%		1,9583	AV

(f) Scenario 2

	Weights		Priority score		
	Factor	Dimension	Score	Factor	Dimension
T/EC-1	4,17%	12,50%	3	0,1250	0,2500
T/EC-2	4,17%		1	0,0417	
T/EC-3	4,17%		2	0,0833	
ENV-1	4,17%	12,50%	3	0,1250	0,2500
ENV-2	4,17%		1	0,0417	
ENV-3	4,17%		2	0,0833	
SOC-1	18,75%	75,00%	1	0,1875	1,1250
SOC-2	18,75%		3	0,5625	
SOC-3	18,75%		1	0,1875	
SOC-4	18,75%		1	0,1875	
	100,00%	100,00%		1,6250	AV

Figure 4.11. *Sensitivity analysis (Step 2). Effects of variations in the distribution of weights per dimension.*

The effects of some possible changes in context, external or internal, are shown in Fig. 4.12. For example, if the market conditions change, and more affordable and cost-effective small-scale hydropower solutions were available, T/EC-1 might result in a higher score. Also might T/EC- 2, if policies strengthen, increasing awareness of hydropower as a solution, and funding opportunities. With a progressive implementation of photovoltaic systems in the area of study as planned, the score of T/EC-3 would increase too. Under these circumstances, the results might reach the highest priority.



Scenario 1: changes in context

	Weights		Priority score		
	Factor	**Dimension**	**Score**	**Factor**	**Dimension**
T/EC-1	11,11%	33,33%	**2**	0,2222	**0,8889**
T/EC-2	11,11%		**3**	0,3333	
T/EC-3	11,11%		**3**	0,3333	
ENV-1	11,11%	33,33%	3	0,3333	**0,7778**
ENV-2	11,11%		1	0,1111	
ENV-3	11,11%		3	0,3333	
SOC-1	8,33%	33,33%	1	0,0833	**0,6667**
SOC-2	8,33%		3	0,2500	
SOC-3	8,33%		2	0,1667	
SOC-4	8,33%		2	0,1667	
	100,00%	100,00%		**2,3333**	**AV**

Figure 4.12. *Sensitivity analysis (Step 2). Effects of variations in the context on Scenario 1.*

4.4.5. Integration of methodologies in sustainable management of wastewater systems

Although this study is focused on hydropower technology, the method and the criteria in step 2 were selected with a broad perspective, to be easily integrated into global energy management at WWTPs. It can also be translatable to other countries. Similar methods could be directly developed by stakeholders, adapting the MCDA method, the criteria and the weights to their specific context (Rezaei et al., 2019; Woltersdorf et al., 2018). The questionnaire provided in Fig. 4.2 could be used as the basis to gather preferences, and the presented case study could serve as an example.

This study presents some limitations, although they could be tackled with further research. Step 1 depends on the accuracy of the data, and the manual processing is time-consuming and prone to human error. Nevertheless, this process allowed the identification of possible modifications of discharge points. If these modifications were feasible, the potential might be higher. Energy recovery with hydropower might still be an option to explore if water circularity is increased as in the Valencia Region. So, the next suggested step would be to validate the results on-site and assess real options to maximize the results.

Concerning step 2 it is important to notice that the SAW method presents important limitations, that should be regarded in the application of this approach to other case studies. As mentioned, the selection of the MCDA method to be applied, the criteria and weighting, will be determined by the results of the analysis of the context. If there are no existing guidelines, with threshold data, other methods, such as PROMETHEE or ELECTRE might be more appropriate for this application. Additionally, unlike other MCDA studies, no alternatives were evaluated, since a comparison was not the purpose at this stage.

A systematic method is provided to wastewater decision-makers, to develop their own methodologies, adapted to their context. In this way, they could complete the information given by the results in step 1, with additional considerations that should be regarded in a sustainability framework (Feiz & Ammenberg, 2017; Sherman et al., 2020). In future work, it would be of interest to include all the alternatives to evaluate, when establishing a decarbonization roadmap.

The findings of this work demonstrate the importance of increasing stakeholders' awareness of the real options for energy recovery at WWTPs. Hydropower could be a "low-hanging fruit" solution, and its potential might not be only hidden in existing wastewater systems (Quaranta et al., 2022), but also in the foreseen ones.

4.5. Conclusions

As climate change poses a challenge, wastewater stakeholders need complete information to evaluate their options, aiming for more sustainable systems. Increasing renewable energy generation is a common goal, and solutions to be applied in the short term are necessary. This article presents a new approach to the application of hydropower to recover energy from wastewater. Unlike previous studies for potential assessment, the proposed methodology includes all three dimensions of sustainability. Alignment with the context is another key issue introduced in this proposal. It is important to determine the decision-makers involved, so the scope of the study can be adapted, and the method and criteria can be tailored to their real options. The proposed method consists of two steps. In step 1, hydropower potential is estimated for each site in the sample. In step 2, after analyzing existing guidelines in the context, a MCDA method is defined and applied for global assessment in a sustainability framework.

The results show that the perspective may be different, if the outcomes from step 1 are put into context in step 2, with a sustainability approach. The results are consistent with previous observations. Biogas presents the highest potential, but its application is limited to a few large plants. Results are also consistent with the still high potential for solar energy in this area, as planned in the regional decarbonization roadmap. Although no direct comparisons can be made, the estimated generation for the 34 sites with hydropower potential (340,472 kWh/year) is within the range of values foreseen for solar energy generation at the smaller plants. Another important finding was that on-site assessment of possibilities, might result in higher values of potential, up to 37.5% in the analyzed sample. If all these results are confirmed, hydropower might be an interesting option to explore.

The contribution of this study is threefold.

(i) It provides a new framework, that can improve the understanding of the role that hydropower could play in the decarbonization of wastewater systems, overcoming the current lack of awareness.

(ii) As a practical contribution, it could serve as a reference for wastewater stakeholders to design similar methodologies adapted to their context. Although the criteria and results presented here are case-specific, the proposed approach can serve as a model for other regions.

(iii) Finally, it is expected to provide useful information to global decision-making tools for the wastewater industry, so as to incorporate hydropower as an option to be explored.

CRediT authorship contribution statement

Rosa M. Llácer-Iglesias: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. P. Amparo López- Jiménez: Writing – review & editing, Supervision. Modesto Pérez- Sánchez: Writing – review & editing, Supervision.

Data availability

Data will be made available on request.

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Appendix B. Supplementary Materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scs.2023.104576.

The following 2 tables show a list of suitable criteria for the purpose of this research, found in the literature, for studies concerning wastewater systems (Table S1) or/and RES (Table S2). The tables indicate the context and the criteria considered for each study analyzed. Criteria that are relevant for WWTPs but were not considered suitable for this study, such as organic matter efficiency removal or sludge production, were not included in this selection.

Table S1. *Studies on MCDA methodologies applied to wastewater systems, that were analyzed during this research to select the sustainability criteria*

Reference	(Palme et al., 2005)	(Curiel-Esparza et al., 2014)	(Mirabi et al., 2014)	(Molinos-Senant et al., 2015)	(Bertanza et al., 2016)	(Castillo et al., 2016)	(Plakas et al., 2016)	(Kamble et al., 2017)	(Ren & Liang, 2017)	(An et al., 2018)	(Arroyo et al., 2018)	(Wolters dorf et al., 2018)	(Saghafi et al., 2019)	(Cossio et al., 2020)
Context $^{(1)}$	SH	WWTP	SW	WWTP	SH	WWTP	WWTP	WWTP	WWTP	SH	WWTP	RRT	WWTP	WWTP
Criteria Economic – Technical Dimension														
Investment cost	√	√	√	√	√	√	√	√	√	√				√
Investment cost (relative)												√		
Operating & mainten. cost	√	√	√	√	√	√	√	√	√	√				√
Payback time														
Complexity design			√		√	√		√				√	√	√
Workforce requirement		√	√	√	√	√	√	√	√	√	√	√	√	√
Replicability			√		√	√		√						
Resilience (ext. changes)	√	√		√	√	√	√	√	√		√	√	√	√
Resilience (int. changes)					√				√				√	√
Applicability										√				
Durability								√				√		
Capital availability												√		√
Funding												√		
Electricity saving	√	√	√		√		√						√	√

Table S1. (Cont.)

Reference	(Palme et al., 2005)	(Curiel-Esparza et al., 2014)	(Mirabi et al., 2014)	(Molinos-Senant et al., 2015)	(Bertanza et al., 2016)	(Castillo et al., 2016)	(Plakas et al., 2016)	(Kamble et al., 2017)	(Ren & Liang, 2017)	(An et al., 2018)	(Arroyo et al., 2018)	(Wolters dorf et al., 2018)	(Saghafi et al., 2019)	(Cossio et al., 2020)
Context (1)	SH	WWTP	SW	WWTP	SH	WWTP	WWTP	WWTP	WWTP	SH	WWTP	RRT	WWTP	WWTP
Criteria Economic – Technical Dimension (cont.)														
Maturity					√				√			√		
Independence of climate										√				
Independence of process					√									
Stability														
Incentives														
Criteria Environmental Dimension														
Carbon footprint	√			√	√			√						√
Land area						√	√	√	√	√	√	√	√	√
Addit. effects on GHGs				√										
Effects on protected areas														
% Self-sufficiency	√													
Additional effects	√		√									√		
Resources recovery	√			√	√			√		√	√	√		√
Water circularity				√							√			√

Table S1. (Cont.)

Reference	(Palme et al., 2005)	(Curiel-Esparza et al., 2014)	(Mirabi et al., 2014)	(Molinos-Senant et al., 2015)	(Bertanza et al., 2016)	(Castillo et al., 2016)	(Plakas et al., 2016)	(Kamble et al., 2017)	(Ren & Liang, 2017)	(An et al., 2018)	(Arroyo et al., 2018)	(Wolters dorf et al., 2018)	(Saghafi et al., 2019)	(Cossio et al., 2020)
Context (1)	SH	WWTP	SW	WWTP	SH	WWTP	WWTP	WWTP	WWTP	SH	WWTP	RRT	WWTP	WWTP
							Criteria Social Dimension							
Noise				√	√	√	√				√			√
Odors		√		√	√	√	√				√		√	√
Visual impact				√		√	√				√			√
Bureaucracy					√							√		
Safety conditions	√	√			√					√		√		
Employment							√		√					
Local community								√				√		√
Public acceptance	√		√	√	√		√	√	√	√	√	√		√
Alignment (general)					√							√		
Alignment (management)												√		
Governmental support					√				√			√		√

Table S1. *Studies on MCDA methodologies applied to wastewater systems, that were analyzed during this research to select the sustainability criteria* ***(Cont.)***

Reference	Ghergh el et al., 2020)	(Liu et al., 2020)	(Munasinghe et al., 2020)	(Delanka-Pedige et al., 2021)	(Foglia et al., 2021)	(Johannesdottir et al., 2021)	(Lizot et al., 2021)	(Ling et al., 2021)	(Omran et al., 2021)	(Salamirad et al., 2021)	(Sucu et al., 2021)	(Trianni et al., 2021)	(Adar et al., 2022)
Context $^{(1)}$	WWTP	WWTP	WWTP	WWTP	RRT	RRT	WWTP	WWTP	WWTP	WWTP	RRT	WWTP	WWTP
						Criteria Economic – Technical Dimension							
Investment cost		√			√	√	√	√	√	√	√	√	√
Investment cost (relative)													
Operating & mainten. cost	√	√			√	√	√	√	√		√	√	√
Payback time							√					√	
Complexity design					√				√			√	
Workforce requirement		√			√		√	√	√	√		√	√
Replicability						√	√	√	√		√	√	√
Resilience (ext. changes)		√		√	√	√	√	√	√	√		√	√
Resilience (int. changes)									√	√		√	√
Applicability												√	√
Durability		√							√				
Capital availability											√	√	
Funding												√	
Electricity saving	√		√	√					√	√		√	

Table S1. (Cont.)

Reference	Ghergh el et al., 2020)	(Liu et al., 2020)	(Munasinghe et al., 2020)	(Delanka-Pedige et al., 2021)	(Foglia et al., 2021)	(Johannesdottir et al., 2021)	(Lizot et al., 2021)	(Ling et al., 2021)	(Omran et al., 2021)	(Salamirad et al., 2021)	(Sucu et al., 2021)	(Trianni et al., 2021)	(Adar et al., 2022)
Context (1)	WWTP	WWTP	WWTP	WWTP	RRT	RRT	WWTP	WWTP	WWTP	WWTP	RRT	WWTP	WWTP
						Criteria Economic – Technical Dimension (cont.)							
Maturity				√	√								
Independence of climate												√	√
Independence of process												√	
Stability		√					√						
Incentives												√	
						Criteria Environmental Dimension							
Carbon footprint	√		√	√	√	√	√	√	√			√	√
Land area	√	√	√	√			√		√		√	√	√
Addit. effects on GHGs			√										√
Effects on protected areas			√									√	
% Self-sufficiency			√	√				√					
Additional effects			√					√				√	
Resources recovery		√	√	√		√						√	
Water circularity			√	√						√			

Table S1. (Cont.)

Reference	Gherghel et al., 2020)	(Liu et al., 2020)	(Munasinghe et al., 2020)	(Delanka-Pedige et al., 2021)	(Foglia et al., 2021)	(Johannesdottir et al., 2021)	(Lizot et al., 2021)	(Ling et al., 2021)	(Omran et al., 2021)	(Salamirad et al., 2021)	(Sucu et al., 2021)	(Trianni et al., 2021)	(Adar et al., 2022)
Context $^{(1)}$	WWTP	WWTP	WWTP	WWTP	RRT	RRT	WWTP	WWTP	WWTP	WWTP	RRT	WWTP	WWTP
Criteria Social Dimension													
Noise									√		√		√
Odors			√					√	√	√	√		√
Visual impact													
Bureaucracy												√	
Safety conditions		√			√	√			√			√	
Employment					√				√				
Local community					√				√				
Public acceptance		√			√	√	√		√		√	√	
Alignment (general)										√		√	
Alignment (management)												√	
Governmental support										√		√	

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[1] Context: Objective of the MCDA method. SH: Evaluation of sludge handling options; WWTP: Selection of the wastewater treatment process technology from a range of alternatives; SW: Evaluation of sewerage options; RRT: Evaluation of resource recovery technologies.

The studies where the objective is the evaluation of renewable energy options at WWTPs are included in Table S2.

Table S2. *Studies on MCDA methodologies applied to renewable energy systems (general or at WWTPs) that were analyzed during this research to select the sustainability criteria*

Reference	(Wang et al., 2009)	(Puleo et al., 2017)	(Lee & Chang, 2018)	(Ilbahar et al., 2019)	(Li et al., 2020)	(Mi & Liao, 2020)	(Nguyen et al., 2020)	(Shao et al., 2020)
Context (1)	RMC	WWTP	RECS	RMC	RECS	RMC	WWTP	RMC
Hydropower (2)	n.a.	NO	YES	YES	YES	n.a.	NO	NO
Criteria Economic – Technical Dimension								
Investment cost	√	√	√	√	√	√	√	√
Investment cost (relative)	√		√	√	√	√		
Operating & maintenance cost	√	√	√	√	√	√	√	√
Payback time	√		√					√
Complexity design								
Workforce requirement			√					
Replicability								
Resilience (external changes)	√		√	√	√	√	√	√
Resilience (internal changes)	√		√	√	√	√	√	
Applicability								
Durability			√					
Capital availability								
Funding			√					
Electricity saving	√	√	√	√	√	√		√
Maturity	√		√	√	√			
Independence of climate			√		√	√		√
Independence of process								
Stability	√		√	√	√	√		
Incentives			√					

Table S2. (Cont.)

Reference	(Wang et al., 2009)	(Puleo et al., 2017)	(Lee & Chang, 2018)	(Ilbahar et al., 2019)	(Li et al., 2020)	(Mi & Liao, 2020)	(Nguyen et al., 2020)	(Shao et al., 2020)
Context (1)	RMC	WWTP	RECS	RMC	RECS	RMC	WWTP	RMC
Hydropower (2)	n.a.	NO	YES	YES	YES	n.a.	NO	NO
Criteria Environmental Dimension								
Carbon footprint reduction	√	√	√	√	√	√	√	√
Land area	√		√	√	√	√		√
Additional effects on GHGs								
Effects on protected areas			√		√			√
% Self-sufficiency		√						
Additional effects	√		√					√
Resources recovery								
Water circularity								
Criteria Social Dimension								
Noise	√		√		√			√
Odors								
Visual impact			√		√			√
Bureaucracy								
Safety conditions	√		√	√	√			
Employment	√		√	√	√	√		
Local community	√		√	√	√			√
Public acceptance	√		√	√	√	√		
Alignment (general)								
Alignment (management)								
Governmental support			√		√			√

Table S2. *Studies on MCDA methodologies applied to renewable energy systems (general or at WWTPs) that were analyzed during this research to select the sustainability criteria* ***(Cont.)***

Reference	(Abdel-Basset et al., 2021)	(Da Ponte et al., 2021)	(Elkadeem et al., 2021)	(Fetanat et al., 2021)	(Fonseca et al., 2021)	(John et al., 2021)	(Liu et al., 2021)	(Buller et al., 2022)
Context (1)	RECS	RMC	RECS	WWTP	RECS	RECS	WWTP	WWTP
Hydropower (2)	NO	YES	NO	NO	NO	YES	NO	NO
Criteria Economic – Technical Dimension								
Investment cost	√	√	√	√	√	√	√	√
Investment cost (relative)		√	√	√		√		√
Operating & maintenance cost	√	√	√	√	√	√	√	√
Payback time		√	√					√
Complexity design		√	√					
Workforce requirement		√						
Replicability		√		√				
Resilience (external changes)		√	√					
Resilience (internal changes)		√	√					
Applicability		√		√				
Durability		√						
Capital availability		√						
Funding		√						
Electricity saving	√	√				√	√	√
Maturity	√	√	√			√		
Independence of climate		√	√			√	√	
Independence of process								
Stability	√	√						
Incentives		√						

Table S2. (Cont.)

Reference	(Abdel-Basset et al., 2021)	(Da Ponte et al., 2021)	(Elkadeem et al., 2021)	(Fetanat et al., 2021)	(Fonseca et al., 2021)	(John et al., 2021)	(Liu et al., 2021)	(Buller et al., 2022)
Context [(1)]	RECS	RMC	RECS	WWTP	RECS	RECS	WWTP	WWTP
Hydropower [(2)]	NO	YES	NO	NO	NO	YES	NO	NO
Criteria Environmental Dimension								
Carbon footprint reduction	√	√	√		√	√		
Land area	√	√	√			√		
Additional effects on GHGs								
Effects on protected areas		√						
% Self-sufficiency		√	√		√		√	√
Additional effects	√	√		√	√	√		
Resources recovery							√	
Water circularity								
Criteria Social Dimension								
Noise		√						
Odors								
Visual impact		√						
Bureaucracy								
Safety conditions		√		√	√			
Employment	√	√		√				
Local community	√	√		√				
Public acceptance		√	√	√				
Alignment (general)	√	√						
Alignment (management)	√	√						
Governmental support		√		√				

[1] Context: Objective of the study.

RMC = Review of studies on MCDA methods applied to renewable energy systems (general application);
RECS = Case study, applying a MCDA method to evaluate renewable energy options (particular application, other than wastewater system);
WWTP = Studies on MCDA methods applied to wastewater systems to evaluate renewable energy options (particular application, wastewater system).

[2] Hydropower technology is included in the evaluation as an option of RES. n.a.= not applicable.

Chapter 5
Results and Discussion

This chapter presents a general discussion of the results obtained throughout this thesis. Detailed results at each stage of the research process have been shown and discussed in each of the three publications. In this chapter, these results are summarized, and an overall discussion is given and related to the objectives described in section 1.2.

This study sought to determine a methodology to assess the potential of hydropower application to wastewater treatment plants (WWTPs), regarding different aspects of sustainability. Figure 5.1 shows the whole research process followed during this Ph.D., with the three main stages of research (contextualization, methodology development, and case study application), the steps included in each of them, as well as their correspondence with the objectives and with the three publications included as Chapters 2, 3 and 4.

The **first stage (contextualization)** corresponds to ***objectives 1, 2, and 3***, and included the following parallel steps:

- Initially, the general context was analyzed (***objectives 1 and 2***), identifying the research gap addressed throughout this research. A review of the state-of-the-art was carried out in two research lines. On the one hand, on the energy demand for wastewater treatment, factors, and trends, identifying available options for renewable energy generation applicable to this industry in the short term. On the other hand, on the application of hydropower technology at a small scale to recover energy from existing networks. With this review (***Publication I***), it was observed that the existing theoretical studies on hydropower might be completed with a broader and more applied approach, whereas the holistic energy tools for WWTPs might be provided with more detailed information about the practical possibilities of hydropower. Thus, the next steps in this research aimed to start to build a bridge between them.

- Besides, a comprehensive search of real case studies applying hydropower to WWTPs was conducted (***objective 3***). However, one finding during this contextualization stage was the lack of awareness about hydropower within the wastewater industry, even in the consulted references. This led to the need of broadening the search so, a broader approach was progressively introduced, searching beyond the academic literature, to identify as many existing sites as possible. To complete the framework, the energy profiles and performances of the identified CS were also evaluated. In ***Publication I*** energy self-sufficiency indicators were applied, and their renewable energy profiles were analyzed. In ***Publication II***, the technical data of the installed hydropower systems were examined, and their energy generation and capacity factors were evaluated.

The **second stage (methodology development)** corresponds to ***objectives 4, 5, and 6***. The proposed methodology consists of 2 steps:

- Firstly, existing methodologies for hydropower potential assessment addressed to wastewater governance stakeholders were analyzed (***objective 4***). After a comparison with the existing background of real CS completed during the previous stage, step 1 of the proposed methodology ***(objective 5)*** was presented in ***Publication II.*** Like all other previous assessment methodologies, this step only regards technical aspects, but some modifications were introduced with a novel approach. Moreover, the results from both, ***Publication I and II,*** had already highlighted the need to also consider environmental and social factors in the decision-making process, which led to develop further the methodology in the second step.
- So secondly, in the following step of the proposed methodology, a MCDA method was developed for global assessment with a sustainable approach (***objective 6***). This method introduces factors in the decision-making process considering all three dimensions of sustainability (economic, environmental, and social). In this way, the results of step 1 are put in context with a broader perspective, other than merely economic feasibility. This step 2 was presented in ***Publication III.***

Finally, according to ***objective 7***, the ***third stage (case study application)***, corresponds to the practical application of the methodology, proposed in alignment with the existing guidelines (PDSEAR). These results were included in ***Publication III***. This article completes the research with the application of both steps of this methodology to a case study, a group of 186 WWTPs in the region of Valencia, selected according to their management model.

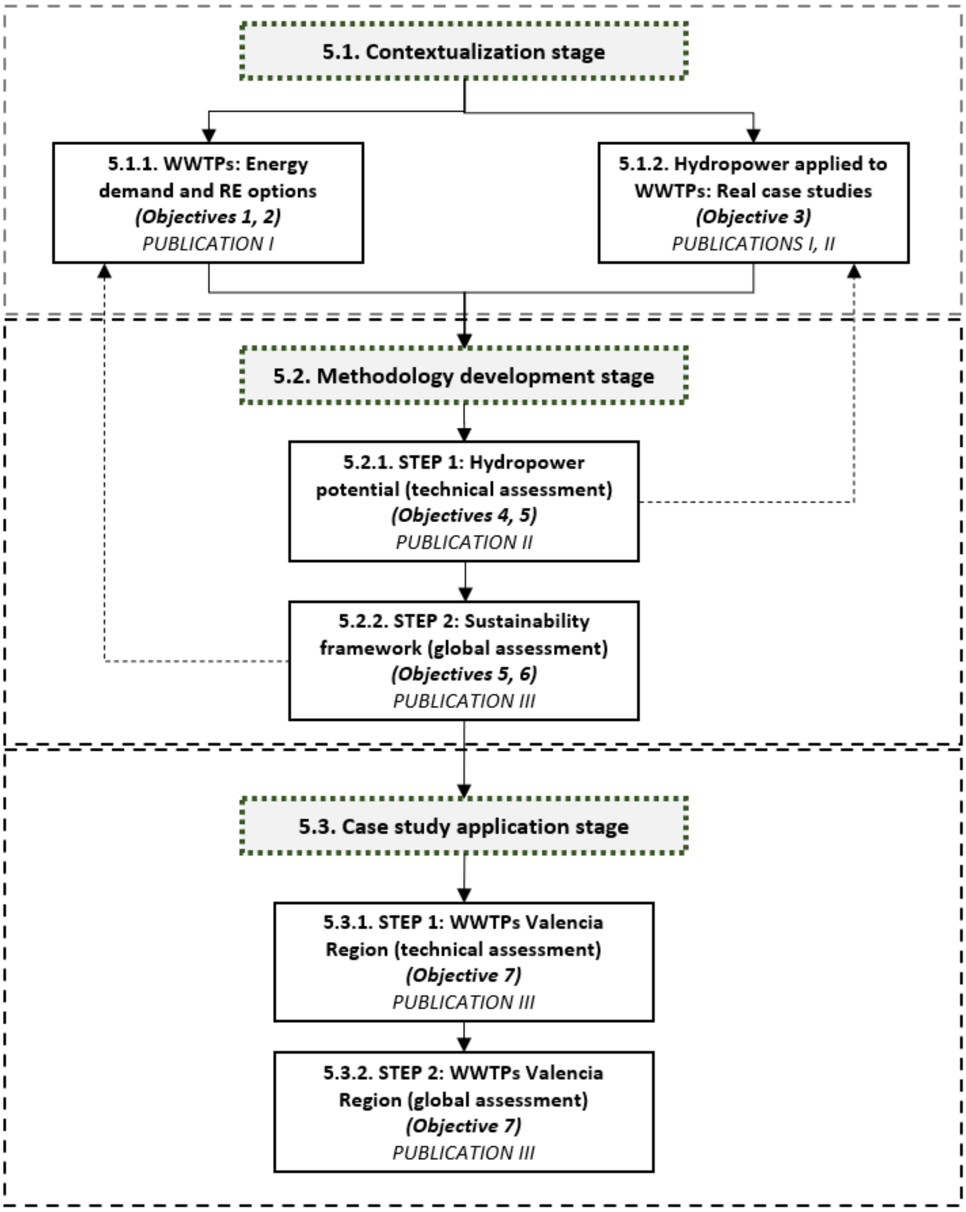


Figure 5.1. *Stages followed during this thesis to reach the research objectives.*

5.1. Contextualization stage

The contextualization stage corresponds to ***objectives 1, 2, and 3***, and the results obtained during this stage were published in ***Publication I***, and ***Publication II***.

5.1.1. Wastewater Treatment Plants: Energy Demand and Renewable Energy Options

According to ***objectives 1 and 2***, the general context is analyzed in ***Publication I,*** "*Energy Self-Sufficiency Aiming for Sustainable Wastewater Systems: Are All Options Being Explored?*", identifying the research gap addressed throughout this research.

This article presents the results of the review of the state of the art of renewable energy options currently applied to wastewater systems, with a special focus on hydropower. Research on energy recovery from wastewater is promising, although the consideration of mature technologies for renewable energy generation is necessary to take action in the short term.

All data in the revised literature indicated that energy demand for wastewater treatment is currently high and in the next decade is expected to increase.

Mature technologies for renewable energy generation include CHP from biogas, solar, wind, and hydropower, but as a general rule, there is not a standalone technology that can lead to 100% energy self-sufficiency. CHP from biogas usually shows the highest potential. However, in most countries, the number of WWTPs with this potential is low (the reported percentages found range between 5.6% and 19.1%), only in the largest plants. From the analysis conducted, it was 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.

Previous academic studies for hydropower potential assessment in wastewater systems have shown that certainly that potential might not be as high as for other mature technologies. Nevertheless, they have demonstrated that some significant potential exists and some energy, that otherwise would be wasted, could be recovered from wastewater. Most of these studies 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 studies is usually limited. Besides, the rapidly changing circumstances of the current energy market might affect the validity of these results over time.

Thus, another important finding of this stage was that there is a lack of awareness within the wastewater sector, about the possibilities that hydropower could offer. Probably, because of the little information publicly available about the existing experience in this application. Due to this lack of awareness, there is a low demand for this technology from the potential market, in this case, most policy- and decision-makers in the wastewater industry. Consequently, there is a low offer of affordable solutions from manufacturers within the smallest ranges of power and low head options, whilst there could be a large potential market for those.

Hence, to complete the contextualization a deep analysis of existing hydropower applications to WWTPs was conducted.

5.1.2. Hydropower Technology Applied to WWTPs: Real Case Studies

To meet ***objective 3***, an exhaustive search of existing experience in this application was conducted. The search process itself applied a broad approach, and some feedback was introduced during the different steps. Firstly, to identify as many real case studies as possible from publicly available data. Secondly, to gather their energy profiles and performance data.

The results of this stage were also published in ***Publication I,*** "*Energy Self-Sufficiency Aiming for Sustainable Wastewater Systems: Are All Options Being Explored?*", where this new approach is introduced, and in ***Publication II***, "*Hydropower Technology for Sustainable Energy Generation in Wastewater Systems: Learning from the Experience*", where the framework is completed.

This intensive search followed the steps sketched in Figure 5.2. The process was designed regarding concepts of systematic review within the sustainability framework, trying to identify all possible real case studies of hydropower application to wastewater systems existing up to date. As a result of the first screening of the retrieved documents, some feedback was introduced in the methodology, and the search was extended beyond the academic literature. 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. 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.

Finally, for each WWTP identified as a real case study, the search was extended seeking published data about their general energy profile and performance. In the following step, these data were further analyzed to establish proper indicators to enable comparisons and the interpretation of results for the aim of this research.

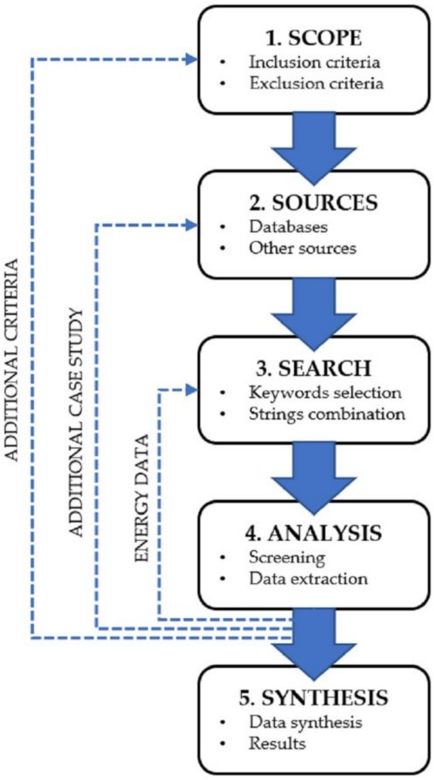


Figure 5.2. *Flowchart of the iterative search methodology adopted.*

Following this iterative process, during this research 49 real case studies were identified (see Table 5.1), many of them not included in previous publications, whereas the largest inventory up to date included only 17 case studies, as the basis to develop the assessment methodology. These results confirm the lack of awareness about this technology in the wastewater industry, together with the academic references, already observed in the general literature. Additionally, the geographical distribution suggests that there is a worldwide interest in this technology.

Table 5.1. *Analysis of real case studies of hydropower applied to WWTPs: Inventory of hydropower systems found during this research.*

ID [1]	Case Study	Location [3]	Year [4]	Installed 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	uesnacht-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

Table 5.1. (Cont.)

ID [1]	Case Study	Location [3]	Year [4]	Installed Power (kW)	Range
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.

[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 an existing case has been displayed as a reference.

[5] N/A: Not Available.

The first issue to notice from the inventory in Table 5.1, is the number of cases and year of installation observed in Switzerland and South Korea, which also arose during the initial 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 and strong policies aiming for decarbonization in South Korea. However, whereas Switzerland is usually regarded in the literature as the pioneer country for this application, the Korean experience has received little attention in previous works.

Regarding this, it is also noticeable that out of Switzerland, where usually the topology is favorable, many cases are located in big cities. 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. Another possible reason could be related to the availability of specialized management resources in larger plants, and higher awareness of the RE options. 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.

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. The gathered information about the year of installation shown in Table 5.1, 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 us to assess more accurately its current performance and therefore, its future potential.

Concerning the technical data of hydropower systems, from the 46 cases with data about their installed power, 17 could be classified as micro-, 22 as mini- and 7 as small-hydropower. None of them fell into the range of pico-hydropower, being 6.6 kW, the lowest power found. These results illustrate that the pico-hydro range and the low-head options have not been fully explored in this application yet.

Additionally, in most of the literature analyzed, the case studies included are merely mentioned as illustrative examples, with no analysis of their actual performance. All this suggested that there might be valuable real experience, which has not been evaluated yet and could be worthwhile to explore further. So, in this study, suitable energy Key Performance Indicators (KPIs) were selected and applied to the energy data obtained from the literature to complete the current framework.

Firstly, the energy profiles at each site were analyzed, trying to identify all RE technologies applied and obtain energy data. Then, energy self-sufficiency indicators were either directly extracted from the literature or easily computed according to their definition, from the total electricity consumption and generation data. Thus, energy self-sufficiency (%), is defined as the ratio:

$$\text{Energy self-sufficiency (\%)} = \frac{\text{Total renewable electric energy generated}}{\text{Total electric energy consumption}} x100 \qquad (5.1)$$

In this study, the KPI calculated were 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. All these results are summarized in Table 5.2.

The analysis of the energy profiles confirmed the conclusions from the studies examined for objectives 1 and 2. In most of the cases where public data were available, other renewable energy technologies were also used at the site (hydropower combined with CHP, solar, or wind).

Table 5.2. *Analysis of real case studies of hydropower applied to WWTPs: Energy self-sufficiency KPIs. RE technologies applied on-site and KPI values of total energy self-sufficiency (%), and hydropower contribution (%) in CS with available data.*

Country/ District	Name of WWTP	Location	Year	Ren. Energy Technologies [4]	% Self-suff.[4]	% Hydropow.[9]	ID
Austria	Plobb -Seefeld [1]	Seefeld Zirl	2005	H	>100%	>100%	1
	Ebswien	Vienna (Simmering)	2009, 2013 [2]	H + S + W [5]	11% [7]	2.6%	2
Switzerland	Chaux-de- Fonds [1]	La Chaux-de-Fonds	2007, 2016 [2]	H + BCHP	65%	N/A	3
	Le Châble Profray	Val de Bagnes, station Verbier (Valais)	1993, 2008 [2]	N/A	N/A	N/A	4
	La Douve 1	Aigle, Leysin (Vaud)	1989, 2000 [2]	N/A	N/A	N/A	5
	La Douve 2	Aigle, Leysin (Vaud)	2001	N/A	N/A	N/A	6
	L'Asse[1]	Nyon (Vaud)	1990	H + BCHP + S	66.1% [7]	33.9% [7]	7
	Grächen	Grächen (Valais)	2011	N/A	N/A	N/A	9
	Engelberg	Engelberg	2010	H + BCHP [6] + S	>100% [7]	65.0% [4]	11
	Morgental (Hofen) [1]	Steinach (St. Gallen)	1916, 2014 [2]	H + BCHP [6] + S + W + T	>100% [7]	N/A	12
	Aïre	Genève	before 2015 [3]	H + BH	N/A	N/A	13
	La Louve [1]	Lausanne	2006	N/A	N/A	N/A	17
Germany	Emmerich (TWE)	Emmerich am Rhein	2000	H + BCHP	N/A	N/A	20
UK	Esholt	Bradford (Yorkshire)	2009	H + BCHP	>100%	5.0%	23

Table 5.2. (Cont.)

Country/ District	Name of WWTP	Location	Year	Ren. Energy Technologies [4]	% Self-suff.[4]	% Hydro-pow.[9]	ID
Spain	Sur	Getafe (Madrid)	before 2014 [3]	H + BCHP	91.2%	2.1% [7,10]	25
Belgium	Brussels-North	Brussels	before 2019 [3]	H + BCHP + S + T	30%	18.0%	28
Australia	North Head	Sydney	2010	H + BCHP	58%	N/A	30
	Gippsland Water Factory [1]	Maryvale (Gippsland Victoria)	2010	H + BCHP	40%	N/A	31
Jordan	As samra	Amman City	2008	H + BCHP	80%	24.0%	32
	As samra II	Amman City	2015	N/A	N/A	N/A	33
South Korea	Asan	Chungnam asan	2000	N/A	N/A	N/A	34
	Cheonan	Chungnam cheonan	2002	N/A	N/A	N/A	35
	Jinhae	Gyeongnam jinhae	2004	N/A	N/A	N/A	36
	Shinshun	Daegu	2005	N/A	N/A	N/A	37
	Seoksu	Gyeonggi Anyang	2007	N/A	N/A	N/A	38
	Seobu	Daegu	2010	H + S	N/A	N/A	39
	Chungju	Chungju	2011	N/A	N/A	N/A	40
	Nan Ji	Seoul	2014	H + BCHP + S + T	51.6% [8]	N/A	41
	Tan Chun	Seoul	before 2017 [3]	H + S + T	51.6% [8]	N/A	42
	Joong Rang	Seoul	2015	H + BCHP + S	51.6% [8]	N/A	43
	Seo Nam	Seoul	2015	H + BCHP + S + T	51.6% [8]	N/A	44

Table 5.2. (Cont.)

Country/ District	Name of WWTP	Location	Year	Ren. Energy Technologies [4]	% Self-suff.[4]	% Hydro-pow.[9]	ID
Taiwan	N/A	Taichung	before 2008 [3]	N/A	N/A	N/A	45
	Hsinchu	Hsinchu	before 2008 [3]	N/A	N/A	N/A	46
USA	Deer Island	Boston (Massachusetts)	2001	H + BCHP + S + W	26%	4.0%	47
	Point Loma	San Diego	2001	H + BCHP	>100%	N/A	48
Canada	Clarkson	Mississauga	2015	H + BCHP	30.8% [7]	1.3% [7]	49

[1] Hydropower inlet flow or electricity output beyond 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. %Self-sufficiency: (annual electricity generated with renewable technologies/annual consumption) x 100%. % Hydropower: (annual electricity generated with hydropower/annual consumption) x 100%.

[8] Global value provided in the literature for the 4 WWTPs in Seoul altogether

[9] Hydropower contribution (%) to energy self-sufficiency.

[10] Values used for calculations correspond to different years.

Concerning the KPI values of total energy self-sufficiency, 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). 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 to optimize the design of hybrid solutions is needed.

The results for the specific KPIs for hydropower (% contribution to self-sufficiency) also suggest that there is not a rule of thumb to determine whether its installation is feasible or not. The registered values ranged from less than 1% to 65%. Therefore, it would be very complicated to establish a single global potential value recommended 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 findings point to the conclusion that no standard solution exists. For each case, the options should be pondered according to its possibilities, from a technical, economic, and strategic point of view.

The technical performance of the identified CS was also analyzed, by calculating, when possible, the capacity factor, defined as:

$$\text{Capacity factor (\%)} = \frac{\text{Energy generated}}{\text{Installed power } 8760} \tag{5.2}$$

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.

This factor was computed for 21 CS obtaining values between 15.5% and 52.7%. These results indicate that actual power output might be lower than expected from the design conditions. They are probably due to the negative effect of flow rate fluctuations on efficiency, as important daily, seasonal, and yearly fluctuations are usual in WWTPs. In one of the identified CS yearly fluctuations were calculated, ranging from 19.7 to 33.8%. If similar data were confirmed for other cases, that would imply that efforts should focus on improving the 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 the 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 5.3. *Analysis of real case studies of hydropower applied to WWTPs: Electricity generation and capacity factor.*

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.

[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.

As a global conclusion of this stage, all the findings demonstrated that there is an existing experience that is not being used to explore hydropower as an option for renewable energy generation in the wastewater sector. 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 developing new assessment methodologies. The comprehensive analysis of existing experience conducted in this research provides a new and more complete framework to develop a methodology with a broader approach.

5.2. Methodology development stage

The methodology development stage corresponds to ***objectives 4, 5, and 6***, and the results obtained during this stage were published in ***Publication II***, and ***Publication III.*** The proposed methodology, consists of 2 steps:

- Step 1 estimates the technical hydropower potential at each site.
- Step 2 evaluates the group of potential sites applying a MCDA method with sustainability criteria.

5.2.1. Step 1: Hydropower Potential (Technical Assessment)

As a necessary step for the development of the methodology, according to ***objective 4,*** previous methodologies for hydropower potential assessment addressed to governance stakeholders were analyzed. The results of this analysis were published in ***Publication II***, "*Hydropower Technology for Sustainable Energy Generation in Wastewater Systems: Learning from the Experience*". The approach in the analyzed studies usually consists of 2 steps:

- 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 general approach is sketched in Figure 5.3. The assumptions made and particular considerations for each study are summarized in Table 5.4 and Table 5.5. In all cases the potential power output is determined by the following general expression:

$$P = \rho \cdot g \cdot Q \cdot H \cdot \eta \qquad (5.3)$$

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.

All the analyzed methodologies have some aspects in common. On the one hand, they are applied to large geographical areas (country or multi-country level) addressing governance stakeholders. However, in some countries, like Spain, other stakeholders at an intermediate level (for example, regional governments) also have an important role in the decision-making process. 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 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, 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.

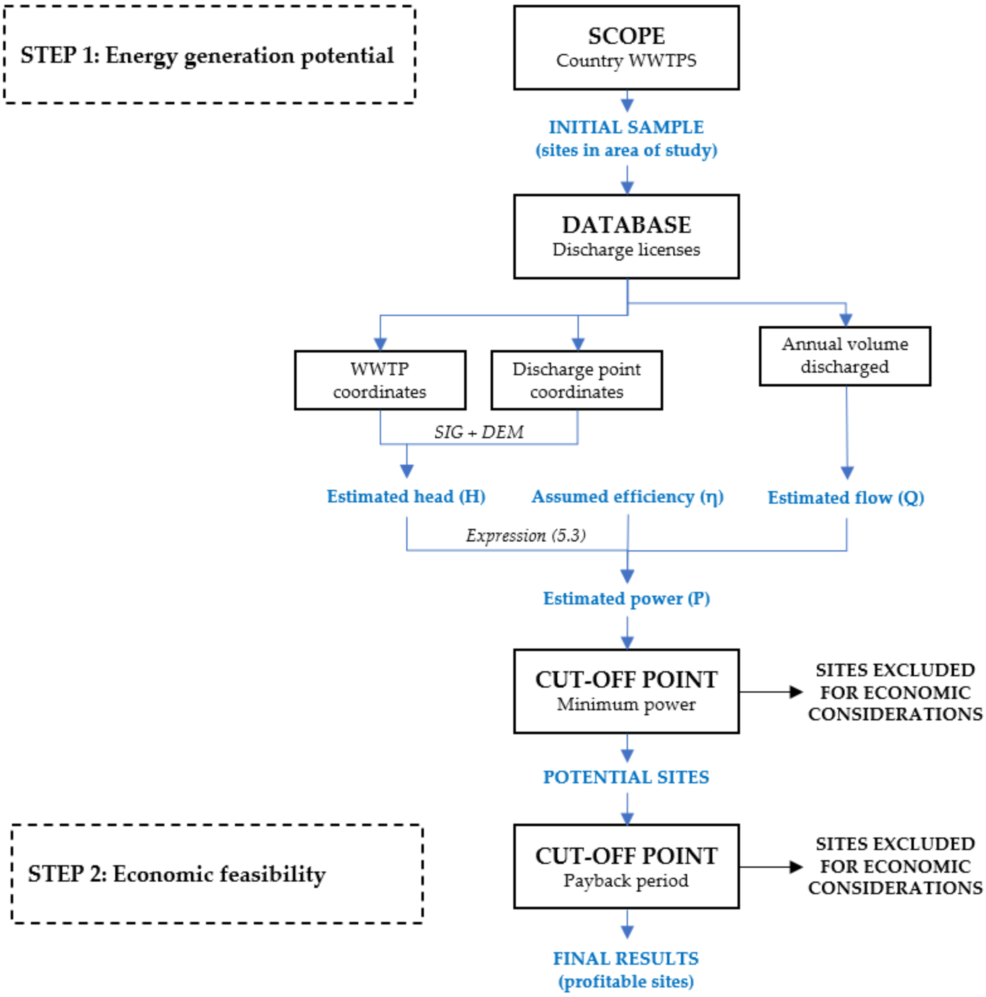


Figure 5.3. *Analysis of existing methodologies for hydropower potential assessment addressed to wastewater stakeholders: General approach.*

Table 5.4. *Analysis of existing methodologies for hydropower potential assessment addressed to wastewater stakeholders: Summary of assumptions made.*

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

Table 5.5. *Analysis of existing methodologies for hydropower potential assessment addressed to wastewater stakeholders: Summary of studies up to date.*

Year	**Dimensions of sustainability considered in the methodology**			**Case study applied**		
	Economical	**Environmental**	**Social**	**Objective and scope**	**Country / Region**	**Management model considered in scope selection**
2014	√	-	-	Global assessment at a country level	Ireland, UK	-
2017	√	-	-	Global assessment at a country level	Switzerland	-
2021	√	-	-	Global assessment at a country level	Spain	-
2021	√	-	-	Global assessment at a country level	Ireland, N. Ireland, Wales, Scotland, Spain, Portugal	-
2022	√	-	-	Global assessment at a country level	South Africa	-
2022	√	√	-	Prioritization ranking at a country level	Lithuania	-
This thesis	√	√	√	**Global assessment at decision-making level**	**Valencia Region (Spain)**	√

Note: The technical assessment is included within the economical dimension.

Additionally, as concluded in the previous stage, the actual performance of existing sites has not been analyzed so far, so neither has been considered in the design of any of these methodologies. Hence, after the examination of the existing methodologies, the assumptions included in them were compared with the background of existing real case studies completed during the contextualization stage. Based on the results of that comparison, in this study, a novel approach is proposed to adapt these methodologies to the sustainability framework.

Hence, all these studies provided a useful basis to develop step 1 of the proposed methodology (technical assessment) which corresponds to ***objective 5***. However, some aspects should be modified. Adjustments at the decision-making level and consideration of driving forces other than economic feasibility in the current market conditions could provide relevant stakeholders with more information about their options. With that, a forward step to more effective application of the technology.

Figure 5.4 illustrates this novel approach for step 1 (technical assessment). This step of the methodology was also presented in ***Publication II***, "*Hydropower Technology for Sustainable Energy Generation in Wastewater Systems: Learning from the Experience*". The basis of the methodology proposed here is focused on the determination of the potential assessment of a sample of WWTPs from an area (also step 1 in the analyzed methodologies).

The results of that assessment should provide the basis to conduct the following phase, global feasibility (step 2). To enable comparisons with the general approach applied in previous methodologies (Figure 5.3), the modifications and new considerations proposed in this study are represented in green for step 1 and orange for step 2.

Like in previous methodologies, H can be estimated using DEM from public data of the coordinates, and an average value for Q from the annual volume discharged. Bearing in mind the fluctuations of the capacity factors observed in the analysis of real case studies (Table 5.3), and the assumptions made in previous methodologies (Table 5.4), a conservative value of 0.5 for the overall efficiency is considered appropriate for estimations, so the potential P can be calculated with expression (5.3). The analysis of real case studies conducted to reach *objective 3* provided the necessary data to validate this step of the method. As a result, all the assumptions made proved to be adequate enough for the estimation of the potential assessment of a number of plants, aim of this study.

In the previous methodologies, a minimum power output of 2-5 kW was applied, based on economic feasibility only. According to the new approach in this research, the cut-off value to determine potential before undertaking the economic study should be based on technical feasibility. According to recent studies hydraulic machines of only a few hundred watts have been recently developed by different manufacturers worldwide. 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. So, this is the proposed value here.

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 of 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. The results of the validation with real CS data mentioned above, also reinforce the idea that establishing a strict absolute value of power as a cut-off point might leave out interesting sites.

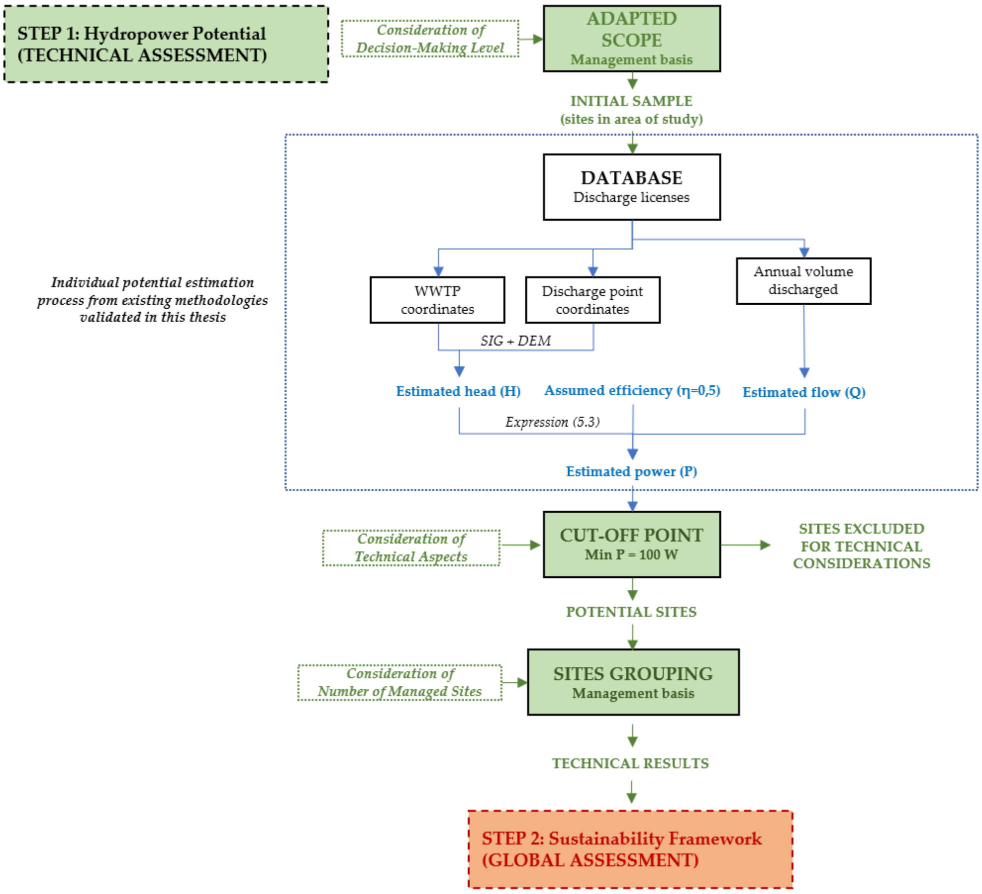


Figure 5.4. *Proposed methodology for hydropower potential assessment in a sustainability framework: Step 1 (technical assessment). Flowchart.*

Alignment with the context is another key issue introduced in this proposal. It is important to determine all the stakeholders involved in wastewater management in the area, so the scope of the study can be adapted. Thus, the area of study should be adjusted to the most likely decision level regarding energy strategies. 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, the results obtained in the contextualization stage (*objectives 1, 2, and 3*) had already highlighted the need to consider driving forces for hydropower implementation at WWTPs, other than economic feasibility. Social and environmental factors should also be introduced in the decision-making process, regarding all important stakeholders involved in wastewater management and modelling to offer a broader perspective. This led to further develop the methodology *(objective 5*), with a second step (*objective 6*).

5.2.2. Step 2: Sustainability Framework (Global Assessment)

To reach ***objective 6***, in step 2 of the proposed methodology (global assessment in a sustainability framework), a new analysis of the context was conducted to define the most suitable method and appropriate economic, environmental, and social factors for the purpose of this study. This second step of the proposed methodology was presented in ***Publication III***, "*Exploring Options for Energy Recovery from Wastewater: Evaluation of Hydropower Potential in a Sustainability Framework*". This article presents the second step of the proposed methodology, a MCDA method for global assessment, which introduces factors in the decision-making process considering all three dimensions of sustainability.

Figure 5.5 shows the flowchart of step 2 in the proposed methodology.

In this proposal, integration into the existing context was considered a crucial issue for effective real application. So, in this Step 2, an analysis of the context is necessary as well, not only to identify the main stakeholders, but also existing governance guidelines, at the same level or higher, and therefore completely align the methodology with the management framework. This analysis will allow us to select a suitable MCDA method and suitable sustainability criteria for the particular application.

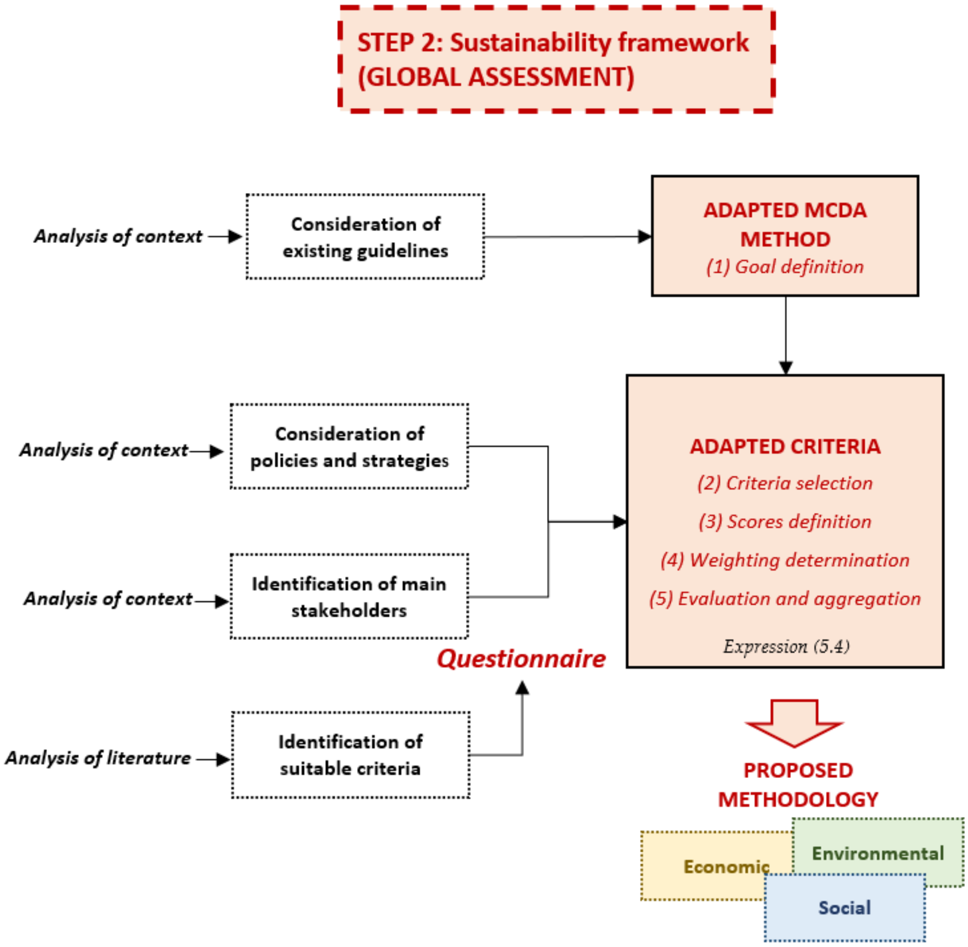


Figure 5.5. *Proposed methodology for hydropower potential assessment in a sustainability framework: Step 2 (global assessment). Flowchart.*

Bearing in mind that for *objective 7* the case study to illustrate the methodology would be selected within the Spanish context, the guidelines in the wastewater governance instrument in Spain (PDSEAR) determined most of the choices made during the development of the methodology, aiming for a full alignment in future practical applications.

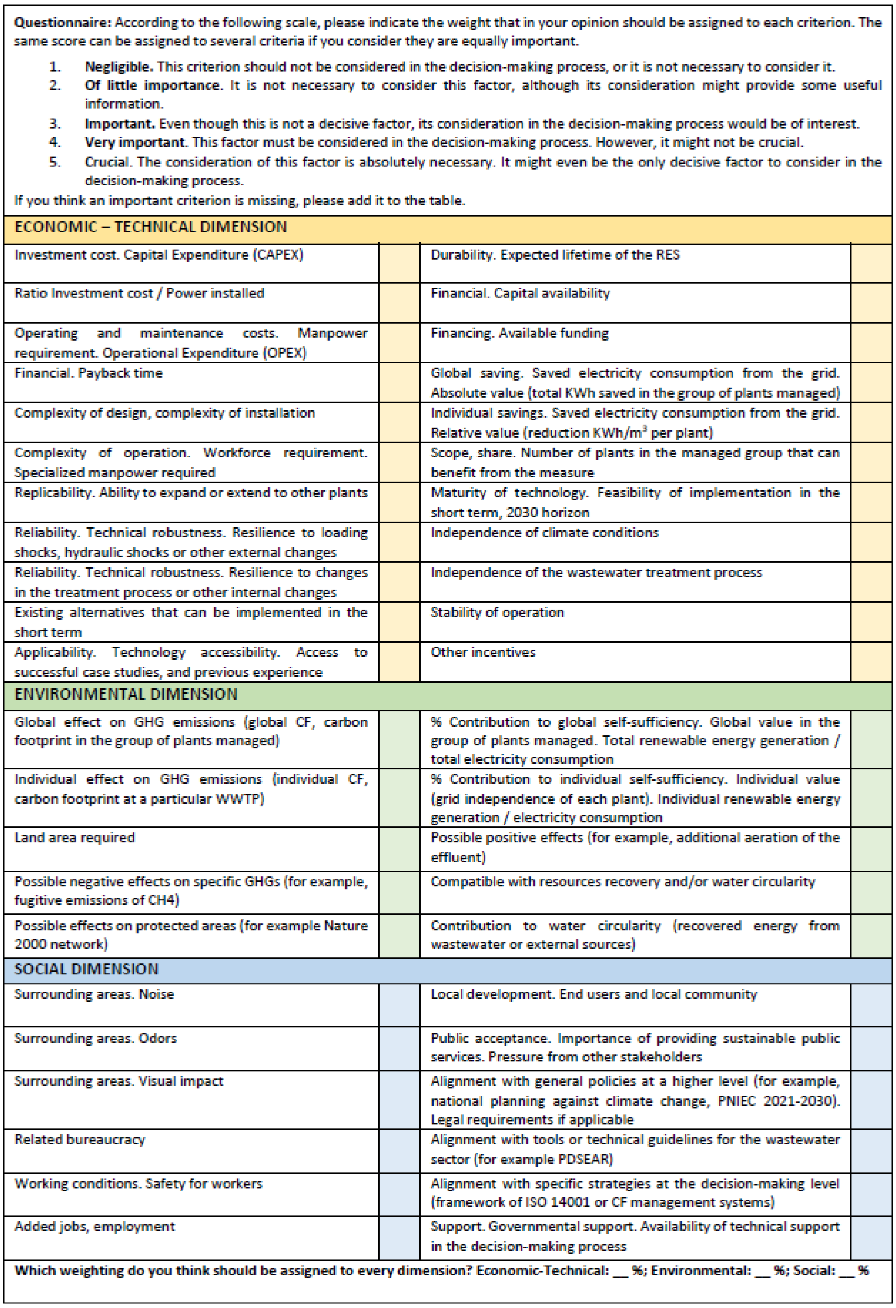
According to this, the weighted sum method (WSM) or simple additive weighting (SAW) was selected as the basis to develop the methodology, tailored for the case study in this research. In this method global score for the scenario or alternative being evaluated can be obtained with the following expression:

$$AV = \sum_{i=1}^{n} w_i \; x_{ij} \qquad (5.4)$$

Where AV is the global score as an aggregate value, n is the number of criteria, w weighting for each criterion i, and x the corresponding score for scenario j.

Concerning the criteria, a new literature review with a focus on MCDA applied to WWTPs and/or RES was conducted at this stage. From that, a range of sustainability criteria were extracted, to select those suitable to be considered in the decision-making process, to install RE technologies at wastewater treatment plants (WWTPs). This information was aggregated in a questionnaire, to gather the opinion of the main stakeholders (Figure 5.6), adding some contributions from the authors according to the proposed approach and scope of this study. This questionnaire tried to be exhaustive, so it could be used to develop similar methods in other contexts. Then, for the purpose of this study and following the model in PDSEAR, the rest of the method was determined as follows:

- Criteria selection: The aim was to define 3–4 criteria per dimension.
- Scores definition: A three-level scale was proposed to rank every criterion, according to 3 possible levels of priority.
- Weighting determination: If there is no available information, a good approach according to the literature is an equal distribution, among dimensions, and within each dimension.
- Evaluation and aggregation: Applying expression (5.4), an aggregate value of priority can be obtained for each scenario evaluated. The AV values range between 1 and 3 and applying a percentual distribution, the highest priority corresponds to $AV \geq 2.3$ and the lowest to $AV \leq 1.6$.



Questionnaire: According to the following scale, please indicate the weight that in your opinion should be assigned to each criterion. The same score can be assigned to several criteria if you consider they are equally important.

1. **Negligible.** This criterion should not be considered in the decision-making process, or it is not necessary to consider it.
2. **Of little importance.** It is not necessary to consider this factor, although its consideration might provide some useful information.
3. **Important.** Even though this is not a decisive factor, its consideration in the decision-making process would be of interest.
4. **Very important.** This factor must be considered in the decision-making process. However, it might not be crucial.
5. Crucial. The consideration of this factor is absolutely necessary. It might even be the only decisive factor to consider in the decision-making process.

If you think an important criterion is missing, please add it to the table.

ECONOMIC – TECHNICAL DIMENSION			
Investment cost. Capital Expenditure (CAPEX)		Durability. Expected lifetime of the RES	
Ratio Investment cost / Power installed		Financial. Capital availability	
Operating and maintenance costs. Manpower requirement. Operational Expenditure (OPEX)		Financing. Available funding	
Financial. Payback time		Global saving. Saved electricity consumption from the grid. Absolute value (total KWh saved in the group of plants managed)	
Complexity of design, complexity of installation		Individual savings. Saved electricity consumption from the grid. Relative value (reduction KWh/m^3 per plant)	
Complexity of operation. Workforce requirement. Specialized manpower required		Scope, share. Number of plants in the managed group that can benefit from the measure	
Replicability. Ability to expand or extend to other plants		Maturity of technology. Feasibility of implementation in the short term, 2030 horizon	
Reliability. Technical robustness. Resilience to loading shocks, hydraulic shocks or other external changes		Independence of climate conditions	
Reliability. Technical robustness. Resilience to changes in the treatment process or other internal changes		Independence of the wastewater treatment process	
Existing alternatives that can be implemented in the short term		Stability of operation	
Applicability. Technology accessibility. Access to successful case studies, and previous experience		Other incentives	
ENVIRONMENTAL DIMENSION			
Global effect on GHG emissions (global CF, carbon footprint in the group of plants managed)		% Contribution to global self-sufficiency. Global value in the group of plants managed. Total renewable energy generation / total electricity consumption	
Individual effect on GHG emissions (individual CF, carbon footprint at a particular WWTP)		% Contribution to individual self-sufficiency. Individual value (grid independence of each plant). Individual renewable energy generation / electricity consumption	
Land area required		Possible positive effects (for example, additional aeration of the effluent)	
Possible negative effects on specific GHGs (for example, fugitive emissions of CH4)		Compatible with resources recovery and/or water circularity	
Possible effects on protected areas (for example Nature 2000 network)		Contribution to water circularity (recovered energy from wastewater or external sources)	
SOCIAL DIMENSION			
Surrounding areas. Noise		Local development. End users and local community	
Surrounding areas. Odors		Public acceptance. Importance of providing sustainable public services. Pressure from other stakeholders	
Surrounding areas. Visual impact		Alignment with general policies at a higher level (for example, national planning against climate change, PNIEC 2021-2030). Legal requirements if applicable	
Related bureaucracy		Alignment with tools or technical guidelines for the wastewater sector (for example PDSEAR)	
Working conditions. Safety for workers		Alignment with specific strategies at the decision-making level (framework of ISO 14001 or CF management systems)	
Added jobs, employment		Support. Governmental support. Availability of technical support in the decision-making process	

Which weighting do you think should be assigned to every dimension? Economic-Technical: __ %; Environmental: __ %; Social: __ %

Figure 5.6. *Proposed methodology for hydropower potential assessment in a sustainability framework: Step 2 (global assessment). Questionnaire elaborated to gather stakeholders' preferences about sustainability criteria.*

5.3. Practical application stage

The application of the complete methodology to a selected case study in Spain illustrates an example of how to develop a tailored methodology with the proposed approach, in order to be integrated into the particular context. This corresponds to ***objective 7*** and was included in ***Publication III***, "*Exploring Options for Energy Recovery from Wastewater: Evaluation of Hydropower Potential in a Sustainability Framework*". In this article, the complete methodology is applied to a case study, a group of 186 WWTPs in the region of Valencia, selected according to their management model (direct financing type).

In this study, the Valencia Region on the Spanish Mediterranean coast was selected. The region consists of 3 provinces (Castellón, Valencia, and Alicante), with 487 WWTPs. Figure 5.7 shows the map of the Valencia Region and the distribution of WWTPs.

In the 1990s the regional regulations assigned all wastewater competencies to the regional administration, including planning and coordination, and operation of WWTPs. Since its creation, the Valencian Wastewater Treatment Agency (EPSAR) has been very active, and nowadays, the Valencia Region shows a high level of compliance with the wastewater European regulation. EPSAR is also taking action in a regional decarbonization roadmap, with progressive implementation of RES (CHP from biogas and photovoltaic systems).

The new modeling framework developed in this research is shown in Figure 5.8 with an overview of the complete methodology applied to this case study.

Figure 5.7. *Practical application of the proposed methodology to the case study in Valencia Region (Spain): Map of WWTPs in the Valencia Region (EPSAR, 2022).*

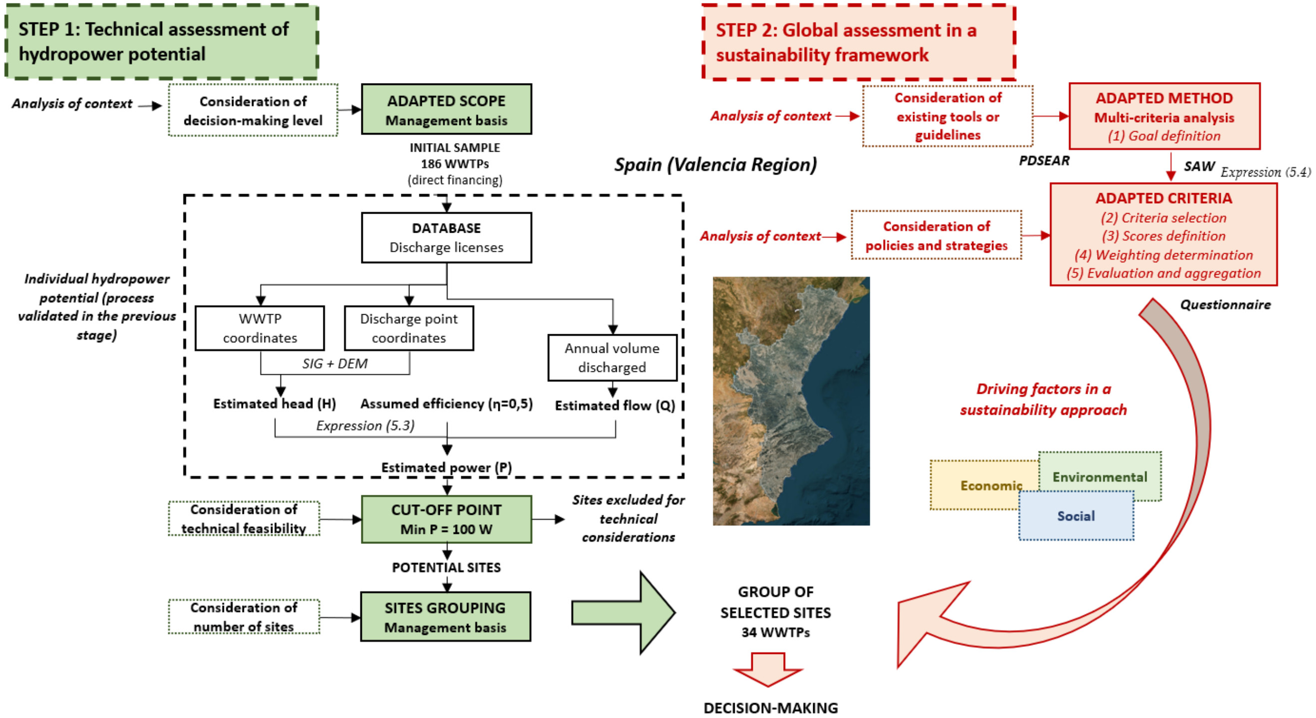


Figure 5.8. *Practical application of the proposed methodology to the case study in Valencia Region (Spain): Methodology overview*

5.3.1. Step 1: Assessment of Hydropower Potential (Valencia Region)

The initial sample to analyze was selected according to the most likely decision-making level for these kinds of strategies. So, it consists of 186 WWTPs, whose management model corresponds to the direct financing type.

The assessment in this step includes technical criteria only, so, unlike other methodologies, no sites were discarded for economic reasons. Fig. 5.9 shows each of the partial outcomes obtained during this step. Some sites were merely discarded because they were not well identified, or their data were not available. Only plants whose effluents are discharged into inland water bodies were considered. Thus, those cases where they are discharged by means of ground infiltration or sea outfalls were discarded too. All the assumptions and estimations made during the process tried to be conservative. After a preliminary screening, a minimum H of 1 m was established, not for technical reasons, but considering the possible inaccuracies in the head estimation method. Additionally, as part of the sensitivity analysis conducted at the final stage of the study, in all cases, the elevations of several points in the surrounding area were also examined, exploring the effects of possible modifications of the discharge point on the available head.

As a result, after the assessment in this step (according to technical criteria), a final group of 34 sites out of the 186 WWTPs showed a potential power higher than 100 W. For this group, the generation of electricity was estimated at 340,472 kWh/year. As expected, this value is far from the current generation from CHP, although it could be regarded as complementary. Furthermore, in the final group of sites, only 1 out of 34 showed potential for CHP, therefore, further implementation of this technology might be limited. Although no direct comparisons can be made, since the size of the initial sample is not the same, this estimated generation is within the range of values foreseen for solar energy generation at the 23 small plants in Castellón (293,402 kWh/year). These results suggest that in future actions of the regional decarbonization roadmap, hydropower might deserve some attention too.

An important finding of the sensitivity analysis of step 1 was that on-site assessment of possibilities, might result in higher values of potential. On the one hand, in this study, initial calculations showed 3 additional sites, finally not included in the results. These sites showed the highest potential values, with an additional generation of 400,464 kWh/year, i.e. duplicating the results. However, according to more updated information nowadays 100% of the effluent in these plants is used for irrigation purposes, so the calculations with their available coordinates would not be offering valid results, and the 3 sites were discarded. On the other hand, if additional modifications of current discharge points at some other sites were feasible, the potential could be higher than the given results, up to 37.5% in the analyzed sample. If these results are confirmed, hydropower might be an interesting option to explore.

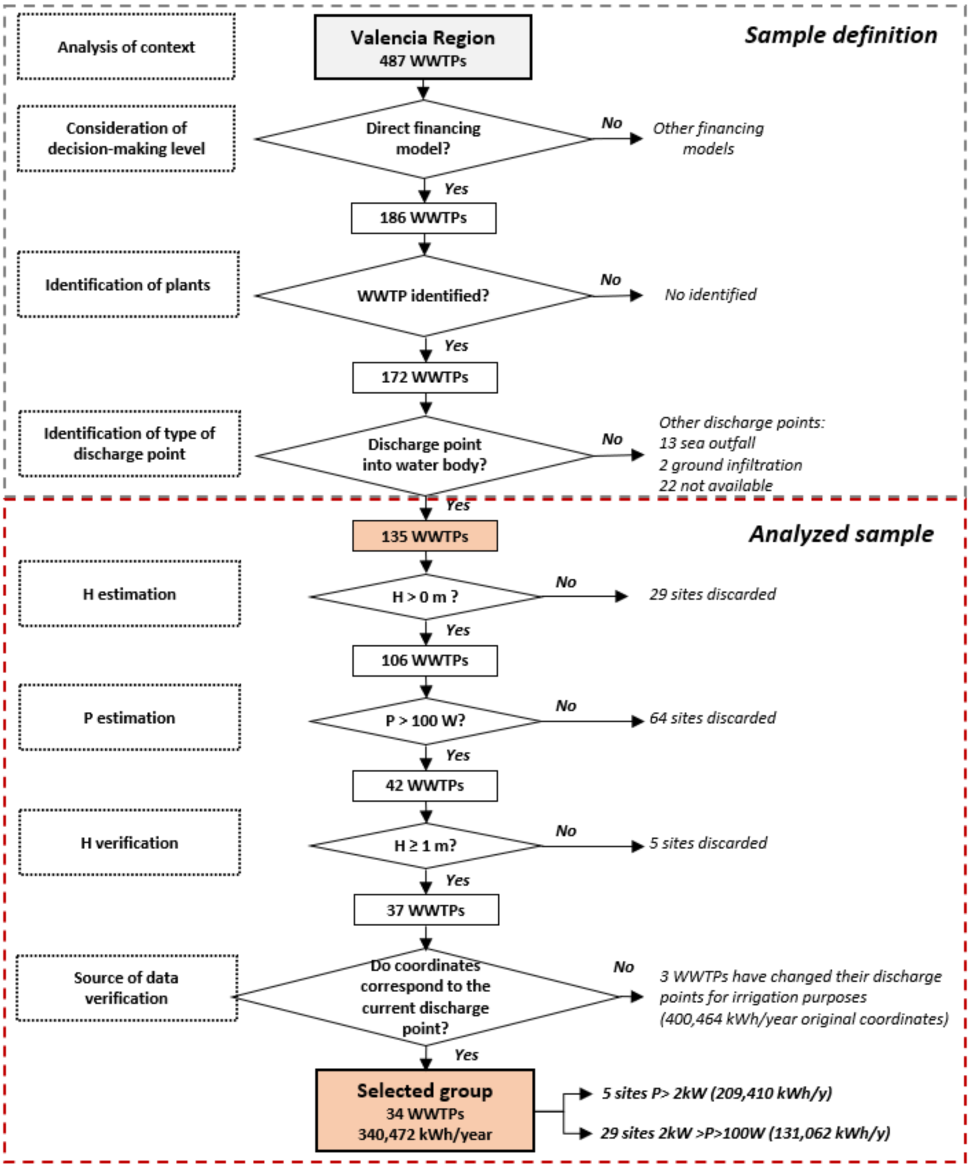


Figure 5.9. *Practical application of the proposed methodology to the case study in Valencia Region (Spain): Process and outcomes in the determination of the technical hydropower potential for the selected sample (Step 1).*

Furthermore, if modifications of discharge points are required for any reason, energy recovery with hydropower might still be an option to explore. For example, if water circularity is increased as in the Valencia Region. Analyzing the inventory of real case studies in Table 5.1, up to 11 of the sites showed particular or unusual configurations. That means 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. These examples illustrate how useful would be for policymakers 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 identifying driving factors for hydropower implementation, other than economic feasibility.

Finally, from the results of this technical assessment, two scenarios were considered to apply the sustainability criteria in step 2:

- Scenario (1) considers the cut-off point proposed in this methodology (based on technical feasibility). The group consists of 34 sites with P>100 W, 5 of them with P>2 kW.
- Scenario (2) considers the lowest cut-off point proposed in previous methodologies (based on economic feasibility). The group includes only the 5 plants with P>2 kW.

5.3.2. Step 2: Assessment in a Sustainability Framework (Valencia Region)

Once the technical assessment was conducted, other criteria were considered to put these results into context. As mentioned, for the case study in this research, a key issue was to align the whole methodology with the PDSEAR guidelines, adapted to the energy focus.

Therefore, a set of criteria that could be suitable for a CS in the Spanish context was selected as described in the previous stage. To gather additional information, the questionnaire (Fig. 5.6) was sent to 2 main stakeholders, EPSAR and one of the companies that monitor the technical performance of WWTPs in the region (LTL). The answers did not show strong preferences, ranking almost all factors as very important or crucial, so, finally, they were only used to validate the consistency of the proposal.

For the assessment according to step 2 (sustainability criteria), 10 criteria were defined (see Figure 5.10). This choice was consistent with the PDSEAR and the questionnaires. All factors were defined in such a way that the higher the indicator, the higher the score, and therefore, the priority. The relative value of each indicator was defined bearing in mind the type of information to provide.

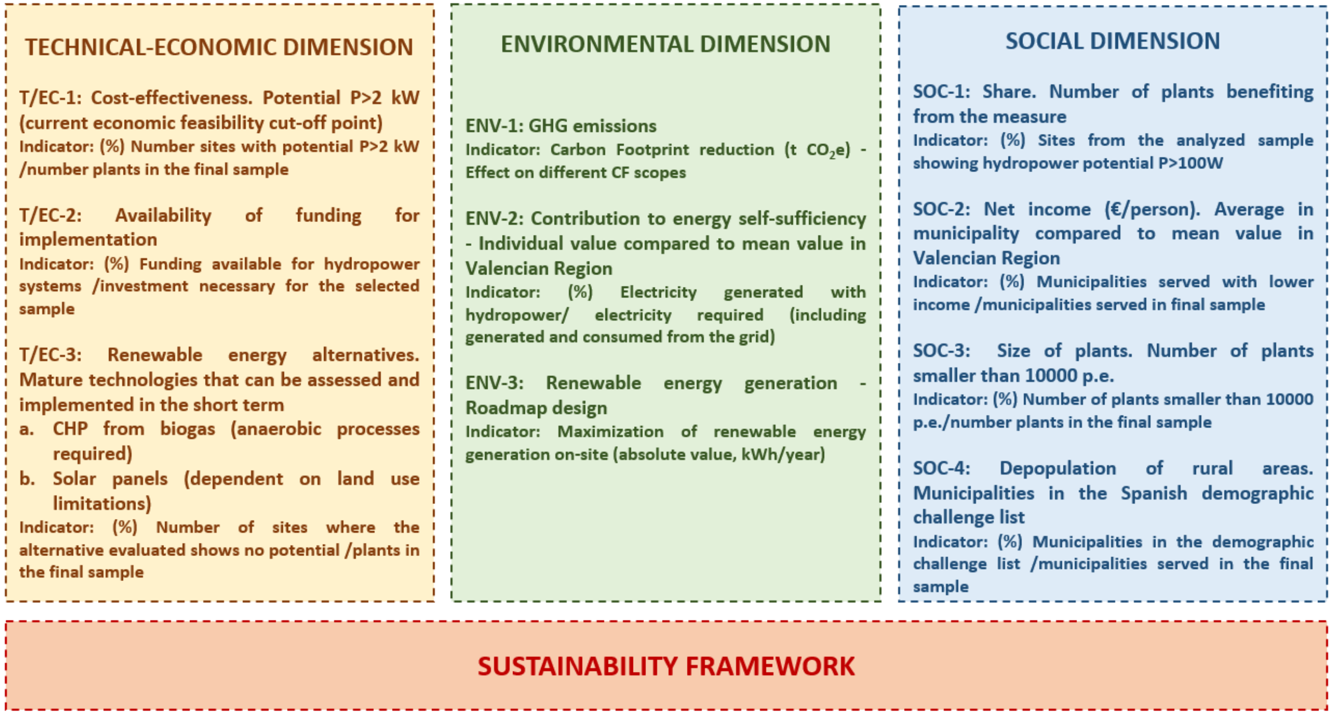
- For the economic dimension (technical considerations were included in this dimension), 3 factors were selected according to the main principles in the European Directive such as cost-effectiveness. As mentioned, to assess individual potential, in this methodology, the lower threshold had been established according to technical feasibility, as P>100 W. However, all other studies applied the threshold for economic feasibility, reported as P>2 kW in the current market conditions. So, this consideration was introduced as an economic factor. In this dimension funding was another factor to consider, and real options to implement ready-in-the-market solutions were also assessed, with a breakdown of every potential technology to ponder.

- For the environmental dimension, 3 factors were selected too. Their selection was focused on energy-related issues, provided there are no interferences with the quality of the effluent. The three of them are somehow related, but each includes several considerations that affect different strategies. The approaches for each indicator are also different (qualitative vs. quantitative, relative vs. absolute value). All of them are already reported by EPSAR, enabling easy monitoring.
- For the social dimension (policy aspects were included in this dimension) 4 factors were selected. In this case, the guidelines in the national strategy from the Ministry were applied.

The definition of the scale of prioritization was established once more according to the PDSEAR model. In particular, the percentile approach, which makes normalization not necessary. This approach is suitable to evaluate the group as a whole, which was one of the requirements in the design of the methodology. Then, priority 1 corresponds to the highest priority, and the corresponding score is 3, whereas priority 3 is the lowest, so the score assigned is 1.

The same weighting to every dimension (33.33%) was assigned, with identical distribution for each criterion within a dimension. This decision was consistent with the literature, PDSEAR, and the questionnaires. The effects of potential modifications on the results were evaluated as part of the sensitivity analysis.

The proposed criteria were applied to the group of sites selected in Step 1, evaluating the 2 scenarios. The aggregated results obtained with the proposed criteria are almost identical in both scenarios (see Figure 5.11). However, the partial scores for each dimension clearly illustrate the differences between the two approaches. Comparing the rankings, in most environmental, and social indicators, the value decreases in scenario 2, although it does not always imply a lower priority. This comparison shows the effects on the results depending on the perspective applied. In any case, the priority results are in the intermediate range. These results are consistent with the still high potential for solar energy in this area, as planned in the regional decarbonization roadmap. But also, that hydropower might be an interesting option to explore next, regardless of the initial approach. The sensitivity analysis also confirmed these observations.



TECHNICAL-ECONOMIC DIMENSION

T/EC-1: Cost-effectiveness. Potential P>2 kW (current economic feasibility cut-off point)

Indicator: (%) Number sites with potential P>2 kW /number plants in the final sample

T/EC-2: Availability of funding for implementation

Indicator: (%) Funding available for hydropower systems /investment necessary for the selected sample

T/EC-3: Renewable energy alternatives. Mature technologies that can be assessed and implemented in the short term

a. CHP from biogas (anaerobic processes required)
b. Solar panels (dependent on land use limitations)

Indicator: (%) Number of sites where the alternative evaluated shows no potential /plants in the final sample

ENVIRONMENTAL DIMENSION

ENV-1: GHG emissions

Indicator: Carbon Footprint reduction (t CO_2e) - Effect on different CF scopes

ENV-2: Contribution to energy self-sufficiency - Individual value compared to mean value in Valencian Region

Indicator: (%) Electricity generated with hydropower/ electricity required (including generated and consumed from the grid)

ENV-3: Renewable energy generation - Roadmap design

Indicator: Maximization of renewable energy generation on-site (absolute value, kWh/year)

SOCIAL DIMENSION

SOC-1: Share. Number of plants benefiting from the measure

Indicator: (%) Sites from the analyzed sample showing hydropower potential P>100W

SOC-2: Net income (€/person). Average in municipality compared to mean value in Valencian Region

Indicator: (%) Municipalities served with lower income /municipalities served in final sample

SOC-3: Size of plants. Number of plants smaller than 10000 p.e.

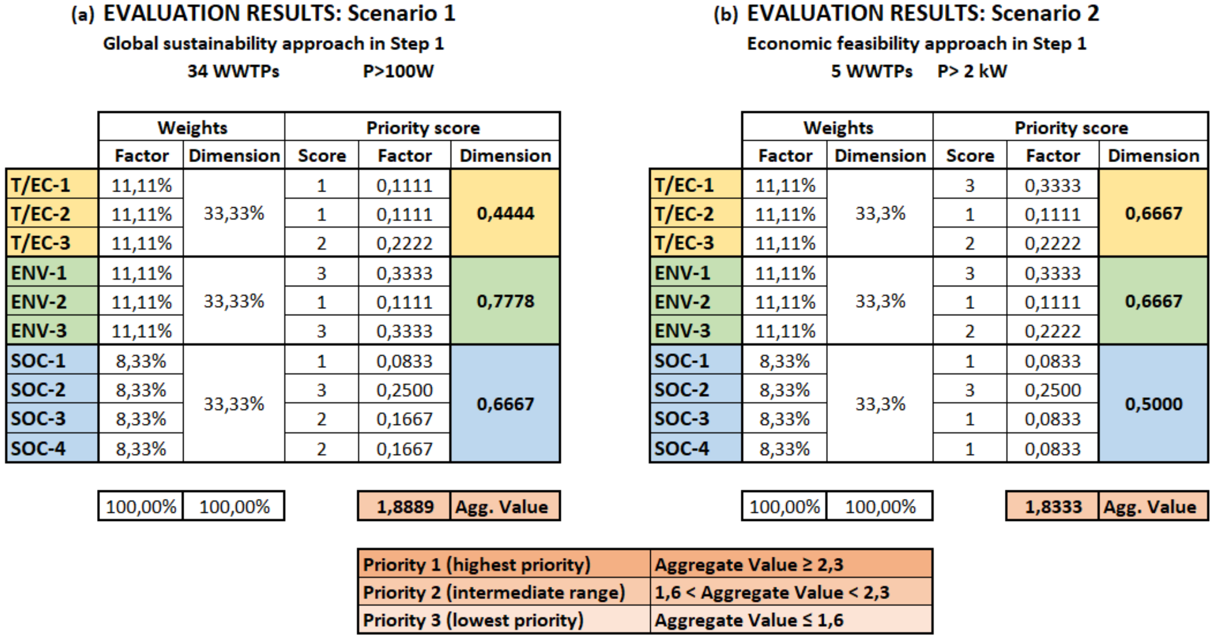
Indicator: (%) Number of plants smaller than 10000 p.e./number plants in the final sample

SOC-4: Depopulation of rural areas. Municipalities in the Spanish demographic challenge list

Indicator: (%) Municipalities in the demographic challenge list /municipalities served in the final sample

SUSTAINABILITY FRAMEWORK

Figure 5.10. *Practical application of the proposed methodology to the case study in Valencia Region (Spain): Sustainability criteria applied (Step 2).*



(a) EVALUATION RESULTS: Scenario 1

Global sustainability approach in Step 1

34 WWTPs P>100W

	Weights		Priority score		
	Factor	Dimension	Score	Factor	Dimension
T/EC-1	11,11%	33,33%	1	0,1111	**0,4444**
T/EC-2	11,11%		1	0,1111	
T/EC-3	11,11%		2	0,2222	
ENV-1	11,11%	33,33%	3	0,3333	**0,7778**
ENV-2	11,11%		1	0,1111	
ENV-3	11,11%		3	0,3333	
SOC-1	8,33%	33,33%	1	0,0833	**0,6667**
SOC-2	8,33%		3	0,2500	
SOC-3	8,33%		2	0,1667	
SOC-4	8,33%		2	0,1667	
	100,00%	100,00%		**1,8889**	**Agg. Value**

(b) EVALUATION RESULTS: Scenario 2

Economic feasibility approach in Step 1

5 WWTPs P> 2 kW

	Weights		Priority score		
	Factor	Dimension	Score	Factor	Dimension
T/EC-1	11,11%	33,3%	3	0,3333	**0,6667**
T/EC-2	11,11%		1	0,1111	
T/EC-3	11,11%		2	0,2222	
ENV-1	11,11%	33,3%	3	0,3333	**0,6667**
ENV-2	11,11%		1	0,1111	
ENV-3	11,11%		2	0,2222	
SOC-1	8,33%	33,3%	1	0,0833	**0,5000**
SOC-2	8,33%		3	0,2500	
SOC-3	8,33%		1	0,0833	
SOC-4	8,33%		1	0,0833	
	100,00%	100,00%		**1,8333**	**Agg. Value**

Priority 1 (highest priority)	**Aggregate Value ≥ 2,3**
Priority 2 (intermediate range)	**1,6 < Aggregate Value < 2,3**
Priority 3 (lowest priority)	**Aggregate Value ≤ 1,6**

Figure 5.11. *Practical application of the proposed methodology to the case study in Valencia Region (Spain): Evaluation results (Step 2). Aggregate values (AV). (a) Scenario 1: Global sustainability approach in Step 1 (34 WWTPs with P>100 W). (b) Scenario 2: Economic feasibility approach in Step 1 (5 WWTPs with P>2kW)*

During the sensitivity analysis of step 2 effects of variations in the distribution of weights and variations in rankings due to changes in the context were evaluated.

Concerning the weights, regardless of the distribution, the results remain in the intermediate priority in most combinations, showing the consistency of the method.

Considering some possible future changes in context, under some circumstances, the results might reach the highest priority. For example, internal changes such as:

- With the progressive implementation of solar systems in the region as planned (since the options for further improvement would be reduced).

Or because of external changes in circumstances:

- If the market conditions change and more affordable and cost-effective small-scale hydropower solutions were available.
- If policies strengthen, increasing awareness of hydropower as a solution, and funding opportunities.

The overall results of the practical application to this CS show that the perspective may be different, if the outcomes from step 1 are put into context in step 2, with a sustainability approach.

Although this study is focused on hydropower technology, the method and the criteria were selected with a broad perspective, to be easily integrated into global energy management at WWTPs. It can also be translatable to other countries. Similar methods could be developed by stakeholders, adapting the criteria and the weights to their specific context. The questionnaire could be used to gather preferences, and the presented case study could serve as an example.

Considering the overall results, it can be concluded that a broader perspective and a sustainability approach were actually needed. Hydropower might deserve more attention. This technology could play a more important role in improving the sustainability of wastewater systems worldwide if efforts in further research are made to tackle its current drawbacks.

Like many other current organizations, WWTPs need to adapt to a rapidly changing context. However, the limitations of budget can often hinder their investments with higher restrictions than in the private sector, especially for smaller plants. Awareness of the technology, demand in the market, 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, i.e., easy to identify and implement. This would enable managers of small wastewater systems to set achievable targets.

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. Therefore, it might contribute to achieving emissions reduction targets, without facing the risks of undertaking significant modifications of the wastewater treatment processes, and facilities or affecting the surrounding environment. Further research would allow us to ascertain the range of possibilities that this technology could offer and the limitations for its application.

Chapter 6
Conclusions

As climate change poses a challenge, wastewater stakeholders need complete information to evaluate the options for their decarbonization roadmaps. Increasing renewable energy generation is crucial, and solutions to be applied in the short term are necessary. This thesis analyzed the existing background of hydropower technology applied to wastewater systems, with a particular focus on practical applications and real case studies experience, to develop a method for potential assessment addressed to governance stakeholders. In alignment with the SDGs, the proposed methodology introduces a novel approach, including all three dimensions of sustainability and the analysis of the context as a key issue during the whole process. This chapter presents the main findings and conclusions of the three stages of this Ph.D. and suggests lines for further research.

6.1. Conclusions

The main conclusion is that hydropower might play a more important role in the decarbonization roadmaps of wastewater systems worldwide if the sustainability approach is applied. From each stage in this research (contextualization, methodology development, and case study application) the following conclusions were drawn, establishing a new framework for this application.

1. Contextualization

1.1. The review during this stage according to ***objectives 1 and 2***, demonstrated that simultaneous actions are needed for the **decarbonization of wastewater systems,** to improve energy efficiency use, and to implement renewable energy technologies. Current research on energy recovery from wastewater is promising, although the consideration of **mature technologies for renewable energy generation** is necessary to take action in the short term. In this context:

I. Current energy demand for wastewater treatment is high and in the next decade is expected to increase.

II. Mature technologies for RE generation include CHP from biogas, solar, wind, and hydropower, but as a general rule, there is not a standalone technology that can lead to 100% energy self-sufficiency. CHP usually shows the highest potential. However, in most countries, the number of WWTPs with this potential is low, only in the largest plants. Other options are needed for the smaller plants too.

III. There is a lack of awareness within the wastewater sector, and also in the academic framework about the possibilities that hydropower could offer. This might be related to the fact that there is little information publicly available about the existing experience in this application.

IV. Due to the lack of awareness, there is a low demand for this technology from the potential market, in this case, most policy- and decision-makers in the wastewater industry. Consequently, there is a low offer of affordable solutions from manufacturers within the smallest ranges of power and low head options, whilst there could be a large potential market for those.

V. Previous academic studies for hydropower potential assessment in wastewater systems have shown that certainly, the potential might not be as high as for other mature technologies. Nevertheless, they have demonstrated that some potential exists and some energy, that otherwise would be wasted, could be recovered from wastewater.

1.2. To meet ***objective 3***, a deep **analysis of existing hydropower applications to WWTPs** was conducted. As a result:

I. During this research 49 real case studies were identified, many of them not included in previous publications, whereas the geographical distribution suggests that there is a worldwide interest in this technology. The largest inventory up to date included only 17 CS, and in most of the literature analyzed, they are merely mentioned as illustrative examples, with no analysis of their actual performance.

II. Concerning the technical data of hydropower systems, from the 46 cases with data about their installed power, 17 could be classified as micro-, 22 as mini-, and 7 as small-hydropower. None of them fell into the range of pico-hydropower, being 6.6 kW, the lowest power found. It is also noticeable that many cases are located in big cities. This could be due to the effect of the economy of scale on economic feasibility, or to the availability of specialized management resources in larger plants, and higher awareness of the RE options.

III. The energy profiles were examined, confirming the conclusions from the studies analyzed for *objectives 1 and 2*. In most of the cases, other renewable energy technologies were also used at the site. KPIs based on the energy self-sufficiency concept were defined and applied to the available data. Only in a few cases over 100% self-sufficiency is achieved, usually as a result of a combination of several technologies. This suggests that self-sufficiency is not a matter of technology choice, but a proper selection of the most suitable combination in each case.

IV. The results for the specific KPIs for hydropower (% contribution to self-sufficiency) also suggest that there is not a rule of thumb to determine whether its installation is feasible or not. The registered values ranged from less than 1% to 65%. Even when this potential seems to be low, factors other than absolute generation capacity and economic feasibility should be considered. For each case, the options should be pondered according to its possibilities, from a technical, economic, and strategic point of view.

V. The technical performance of the identified CS was also analyzed, by calculating the capacity factor. This factor was computed for 21 CS obtaining values between 15.5% and 52.7%. These results indicate that actual power output might be lower than expected from the design conditions. In one of the identified CS yearly fluctuations were calculated, ranging from 19.7 to 33.8%. This analysis indicated that improving machinery efficiency still poses a major challenge, particularly regarding the fluctuations in flow rate.

VI. As a global conclusion of this step, the findings demonstrated that there is an existing experience that is not being used to explore hydropower as an option for RE generation in the wastewater sector. The comprehensive analysis of existing experience conducted in this research provides a new and more complete framework to develop a methodology with a broader approach.

2. Methodology development

2.1. As a necessary step for the development of the methodology, **previous studies for hydropower potential assessment** were analyzed, according to ***objective 4.*** The analysis of methodologies concluded that economic feasibility is usually the only factor considered. However, they provided a useful basis to develop **step 1 of the proposed methodology (technical assessment)** with some modifications, which corresponds to ***objective 5***.

I. Similarly to previous methodologies, H can be estimated using DEM from public data of the coordinates, and an average value for Q from the annual volume discharged. Applying a conservative value of 0.5 for the overall efficiency, the potential P can be calculated. The analysis of real CS conducted to reach *objective 3* provided the necessary data to validate this step of the method, so these estimations proved to be adequate for the aim of this study.

II. In the analyzed methodologies a minimum power output of 2-5 kW was applied, based on economic feasibility only. According to the new approach in this research, the cut-off value to determine the potential before undertaking the economic study should be based on technical feasibility, which nowadays, could be established in an individual minimum of 100 W.

III. Alignment with the context is another key issue introduced in this proposal. It is important to determine the most likely decision level regarding energy strategies, so the scope of the study can be adapted. In this way, in further steps, the proposal considers the evaluation of the selected sites as a group, to benefit from possible economies of scale, not in size but in number.

IV. Moreover, the results obtained in the contextualization stage (*objectives 1, 2, and 3*) had already highlighted the need to consider driving forces for hydropower implementation, other than economic feasibility. Social and environmental factors should also be introduced. This led to further develop the methodology *(objective 5*), with a second step (*objective 6*).

2.2. To reach ***objective 6***, in **step 2 of the proposed methodology (global assessment in a sustainability framework)**, a new analysis of the context was conducted to define the most suitable method and appropriate economic, environmental, and social factors for the purpose of this study.

I. Since the alignment with the context is a key issue in this proposal, it was important to determine the decision-makers involved and the existing guidelines in the area of study, so the MCDA method and criteria could be tailored to their real options. Bearing in mind that for *objective 7* the case study to illustrate the methodology would be selected within the Spanish context, the guidelines in the wastewater governance instrument in Spain (PDSEAR) determined most of the choices made, aiming for a full alignment in future applications.

II. According to this, the SAW method was selected. After a new literature review with a focus on MCDA applied to WWTPs and/or RES, suitable sustainability criteria were extracted, and the information was aggregated in a questionnaire, to gather the opinion of the main stakeholders.

3. Practical application

3.1. The application of the complete methodology to a selected case study in Spain illustrates an example of how to develop a tailored methodology with the proposed approach, in order to be integrated into the particular context. This corresponds to ***objective 7***.

I. The proposed methodology was applied to an initial sample that consists of 186 WWTPs in the Region of Valencia, selected according to the management model (direct financing type).

II. After the assessment according to **step 1 (technical criteria only)** a final group of 34 sites out of the 186 WWTPs showed a potential power higher than 100 W. For this group, the generation of electricity was estimated at 340,472 kWh/year. As expected, this value is far from the current generation from CHP, although is within the range of values foreseen for solar energy generation at the smaller plants, as planned in the regional decarbonization roadmap.

III. An important finding of the sensitivity analysis of step 1 was that on-site assessment of possibilities, might result in higher values of potential. On the one hand, in this study, initial calculations showed 3 additional sites, finally not included in the results since nowadays 100% of the effluent in these plants is used for irrigation purposes. On the other hand, if additional modifications of current discharge points at some other sites were feasible, the potential could be higher than the given results, up to 37.5% in the analyzed sample. If these results are confirmed, hydropower might be an interesting option to explore.

IV. For the assessment according to **step 2 (sustainability criteria)**, 10 criteria were defined. Consistent with the PDSEAR and the questionnaires, 3 of them belonged to the economic dimension (technical considerations included), 3 to the environmental, and 4 to the social one, with equal distribution of weighting. The results show that the perspective may be different, if the outcomes from step 1 are put into context in step 2, with a sustainability approach.

V. During the sensitivity analysis of step 2 effects of variations in the distribution of weights and variations in rankings due to changes in the context were evaluated. Concerning the weights, regardless of the distribution, the results remain in the intermediate priority in most combinations, showing the consistency of the method. Concerning some possible changes in context, under some circumstances, the results might reach the highest priority.

VI. Although this study is focused on hydropower technology, the method and the criteria were selected with a broad perspective, to be easily integrated into global energy management at WWTPs. It can also be translatable to other countries. Similar methods could be developed by stakeholders, adapting the criteria and the weights to their specific context. The questionnaire could be used to gather preferences, and the presented CS could serve as an example.

The final **contribution of this research** is threefold:

(i) It provides a more complete framework, that can improve the understanding of the role that hydropower could play in the decarbonization of wastewater systems, overcoming the current lack of awareness.

(ii) As a practical contribution, it could serve as a reference for wastewater stakeholders to design similar methodologies adapted to their context. Although the criteria and results presented here are case-specific, the proposed approach can serve as a model for other regions.

(iii) Finally, it is expected to provide useful information to global decision-making tools for this industry, to incorporate hydropower as an option to be explored.

Considering the overall results, it can be concluded that a broader perspective and a sustainability approach were actually needed. Hydropower might deserve more attention. This technology could play a more important role in improving the sustainability of wastewater systems worldwide if efforts in further research are made to tackle its current drawbacks.

6.2. Future Research

With the exhaustive analysis of the existing background, this thesis sought to provide a new framework for further research in this application establishing suitable connections to fill the gaps found. Thus, further research on hydropower technology for this application should consider the following:

- Research projects should consider gathering more robust data on the current performance of existing real case studies, involving different stakeholders and learning from the experience.
- Research should also focus on optimizing efficiency performance, particularly regarding the effects of flow rate fluctuations. However, few organizations are willing to take risks implementing new technologies and being pioneers, unless they take part in funded projects. Therefore, research 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. 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 special interest would be the development of affordable market solutions within the micro- and pico-hydropower ranges, with a special focus on low-head options. Reliable hydraulic machinery adapted to different working conditions would benefit not only the wastewater sector but also drinking and irrigation water systems.
- Moreover, the availability of demonstration sites, real or experimental, would also be essential for disclosure to the wastewater management stakeholders, thus overcoming the current lack of awareness.

The limitations of budget can often hinder investments at WWTPs with higher restrictions than in the private sector, especially for smaller plants. 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 a “low-hanging fruit,” as energy efficiency measures in general already are, i.e., easy to identify and implement. This would enable managers of small wastewater systems to set achievable targets in the short term. 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. This could also be the case in developing countries or in periods of uncertainty. Therefore, further research would allow us to ascertain the range of possibilities that the technology could offer and the limitations of its application.

The methodology in this thesis presents some limitations, although they could also be tackled with further research.

- Step 1 depends on the accuracy of the data, and the manual processing is time-consuming and prone to human error. Nevertheless, this process allowed the identification of possible modifications of discharge points. If these modifications were feasible, the potential might be higher. Energy recovery with hydropower might still be an option to explore if water circularity is increased as in the Valencia Region. So, the next suggested step would be to validate the results on-site and assess real options to maximize the results.
- Concerning step 2 a systematic method is provided to wastewater decision-makers, to develop their own methodologies, adapted to their context. In this way, they could complete the information given by the results in step 1, with additional considerations that should be regarded in a sustainability framework. In future work, it would be of interest to include all the alternatives to evaluate, when establishing a decarbonization roadmap.

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 short-term solution to improve sustainability in wastewater systems.

Chapter 7
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