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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.

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

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Nomenclature

Acronyms

AV	Aggregate Value
CHP	Combined Heat and Power
CS	Case Study
DEM	Digital Elevation Model
ELECTRE	ELimination Et Choix Traduisant la REalite
EPSAR	Valencian Wastewater Treatment Agency
GIS	Geographic Information Systems
MCDA	Multi-Criteria Decision Analysis
MCDM	Multi-Criteria Decision Making
PDSEAR	Plan for Wastewater Treatment, Sanitation, Efficiency, Savings and Reuse
PROMETHEE	Preference Ranking Organization METHod for Enrichment Evaluations
RES	Renewable Energy Systems
SAW	Simple Additive Weighting
SDGs	Sustainable Development Goals
WSM	Weighted Sum Method
WWTPs	Wastewater Treatment Plants

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

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.

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 & Jurevičius, 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 Jurevičius (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 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. 1, with an overview of the complete methodology.

3. Materials and methods

3.1. Methodology overview

Fig. 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 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.
- 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 3.2, and a methodology for Step 2 is proposed by developing a MCDA method in Section 3.3, according to the sustainability concept (Oliveira Neto et al., 2018). Then the methodology is applied to a case study in Spain as

Table 1
Relevant academic studies on methodologies for hydropower potential assessment of wastewater systems addressed to urban wastewater governance stakeholders.

Reference	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.

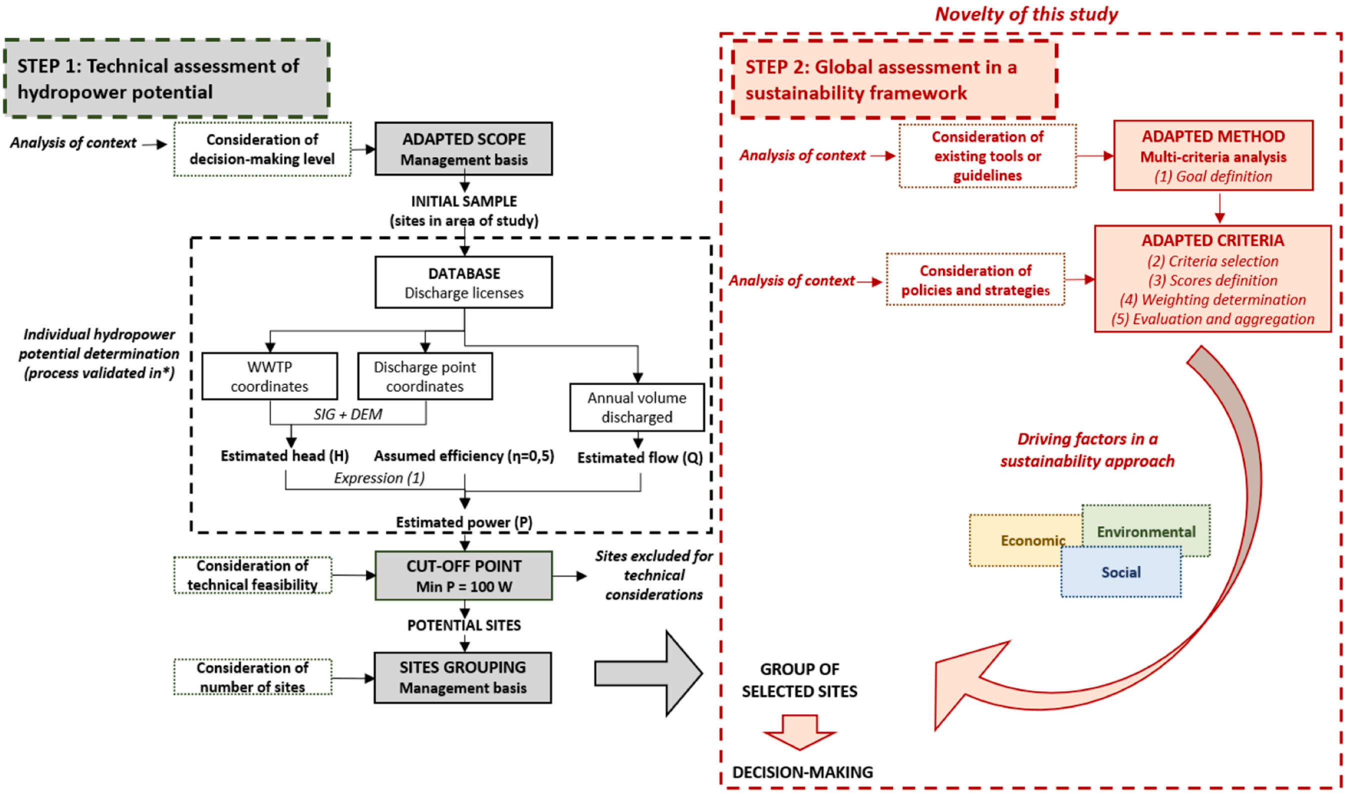


Fig. 1. Methodology overview, adapted from Llácer-Iglesias et al. (2021b) (*).

described in Section 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 1, for each site, the hydropower potential can be determined as:

$$P = \rho \cdot g \cdot Q \cdot H \cdot \eta \quad (1)$$

where P is the power (W), ρ water density (kg/m^3), g acceleration due to gravity (m/s^2), Q volume flow rate (m^3/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 1, where the threshold is established in 2 kW (or 5 kW), based on economic feasibility only.

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 & Jurevičius, 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 & Jurevičius, 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.

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.

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:

$$AV = \sum_{i=1}^{n} w_i \, x_{ij} \tag{2}$$

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.

(1) ***Sustainability criteria application***

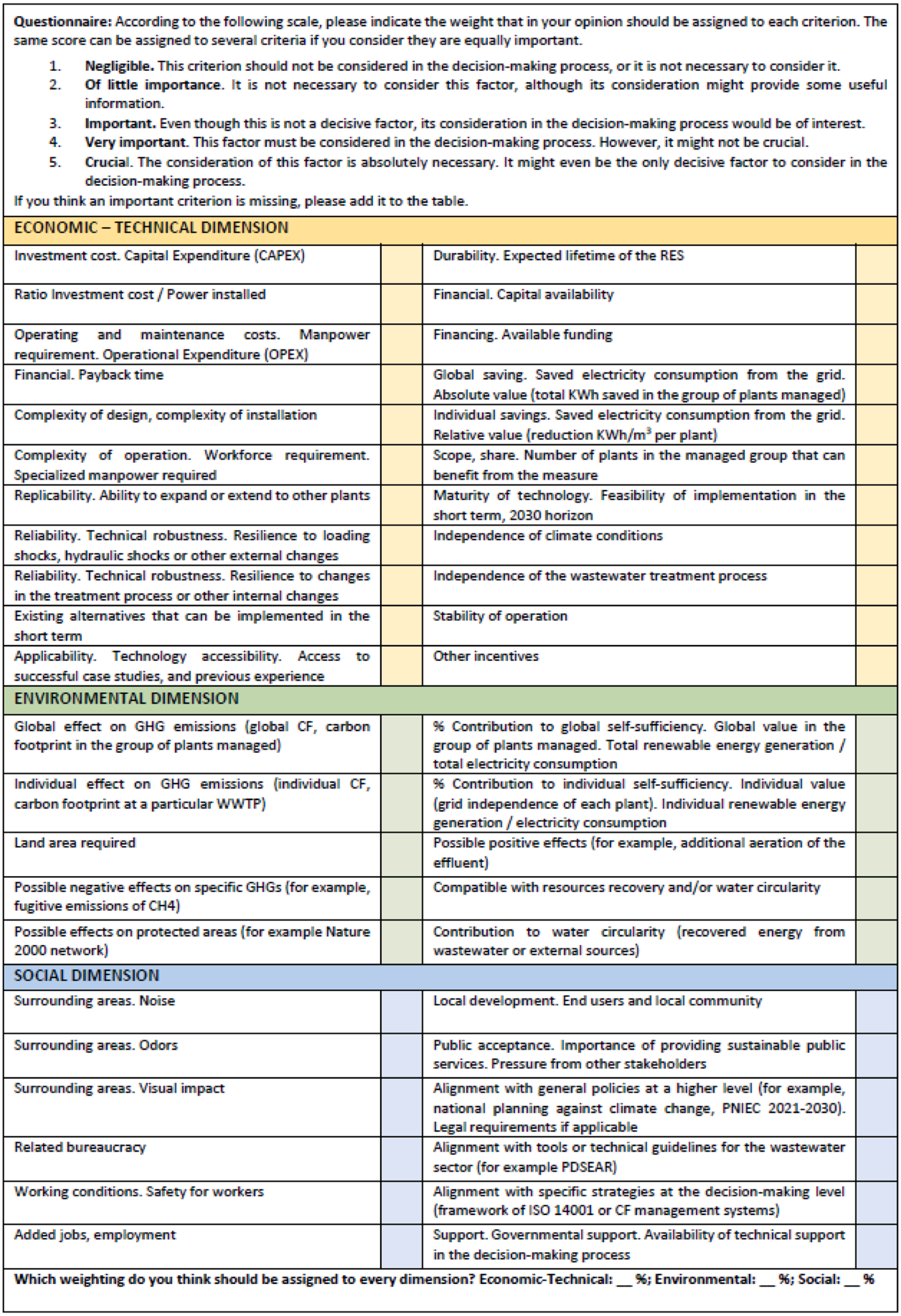
According to the approach of this research, it was considered important to also align the remaining steps of the methodology with the existing guidelines for wastewater governance, adapted to the energy focus. The specific application to the Spanish context is described in Section 4. Nevertheless, there 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.

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. 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



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: __ %

Fig. 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 data.

obtained from the questionnaires are described in Section 4.3.

Finally, the proposed criteria (see Section 4.3.1 and Fig. 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 4.3.1, Figs. 79). 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.

(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.

(5) ***Evaluation and aggregation***

Applying expression (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$\geq$2.3 and the lowest to AV$\leq$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. Results and discussion

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.

4.1.1. 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 1452,177 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 1152,340 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.

4.1.2. Case study data

Detailed data for each WWTP are publicly available on the EPSAŔs 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 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. 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

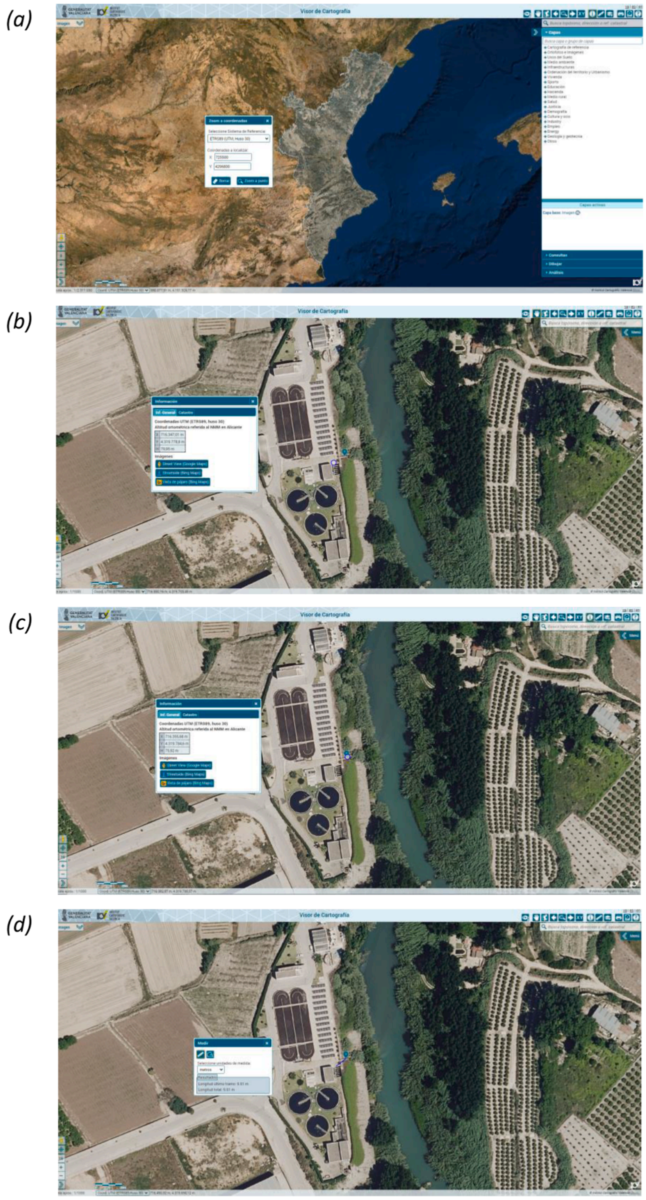


Fig. 3. Step 1. Hydropower potential assessment, H estimation. (a) Geo-visualization tool used (b) WWTP coordinates, including elevation (c) discharge point coordinates, including elevation (d) distance estimation.

stage of the study (see 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.

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 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 4.1.1.), indicates that in future actions, hydropower might deserve some attention too.

Fig. 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.

Finally, as part of the sensitivity analysis conducted in this study (see Section 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, 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.

4.3. *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.

4.3.1. *Case study criteria definition*

Criteria selection. A set of criteria that could be suitable for a case study

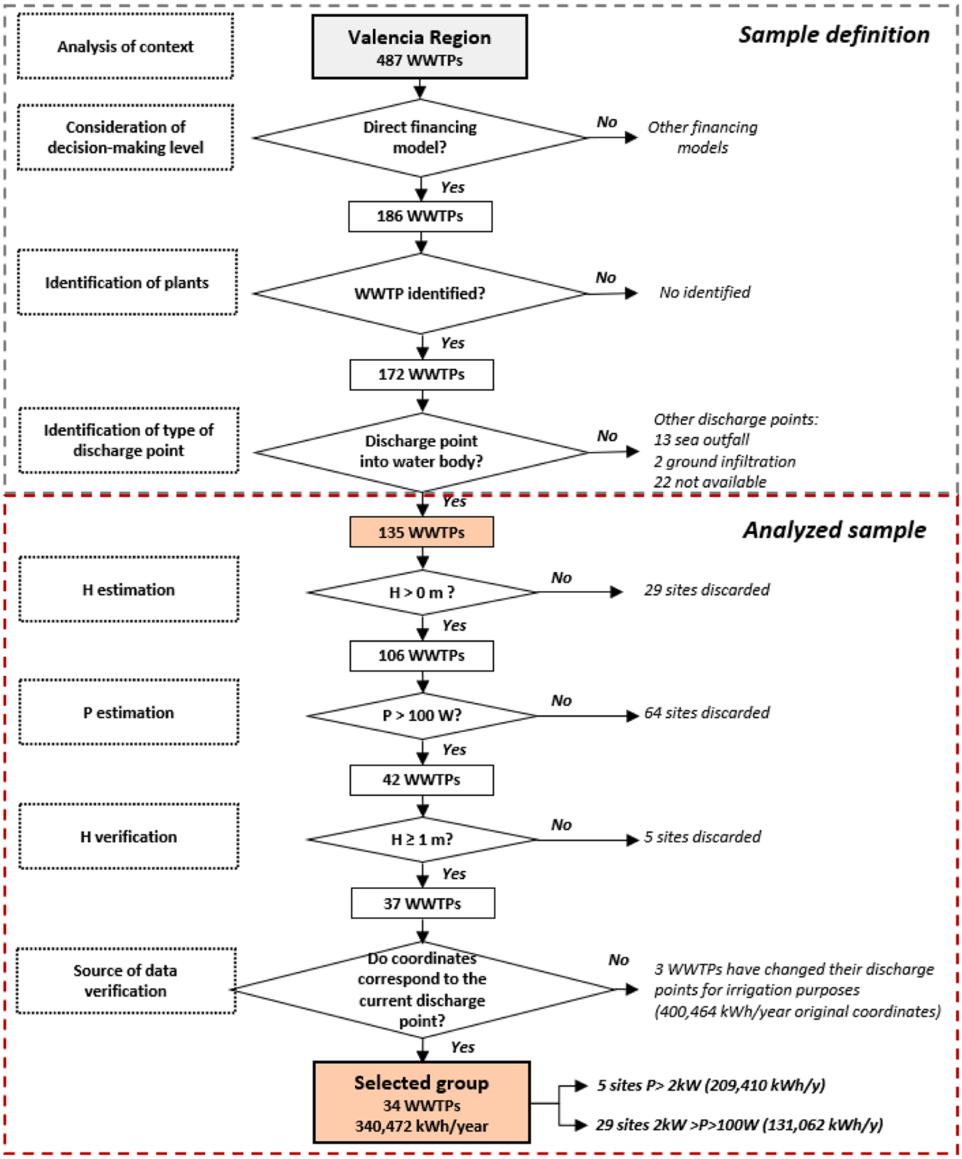


Fig. 4. Step 1. Process and outcomes in the determination of the technical hydropower potential for the selected sample.

in the Spanish context was selected as described in Section 3.3.2. To gather information for the criteria definition, the questionnaire (Fig. 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. 5 summarizes the outcomes of this step.

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. 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 & Jurevičius, 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.

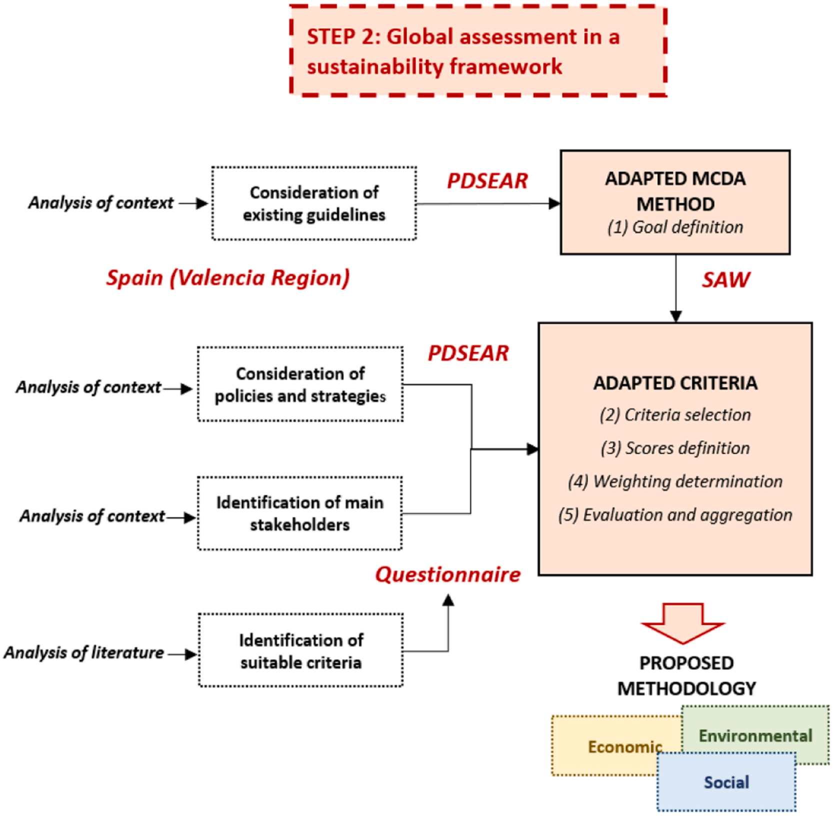
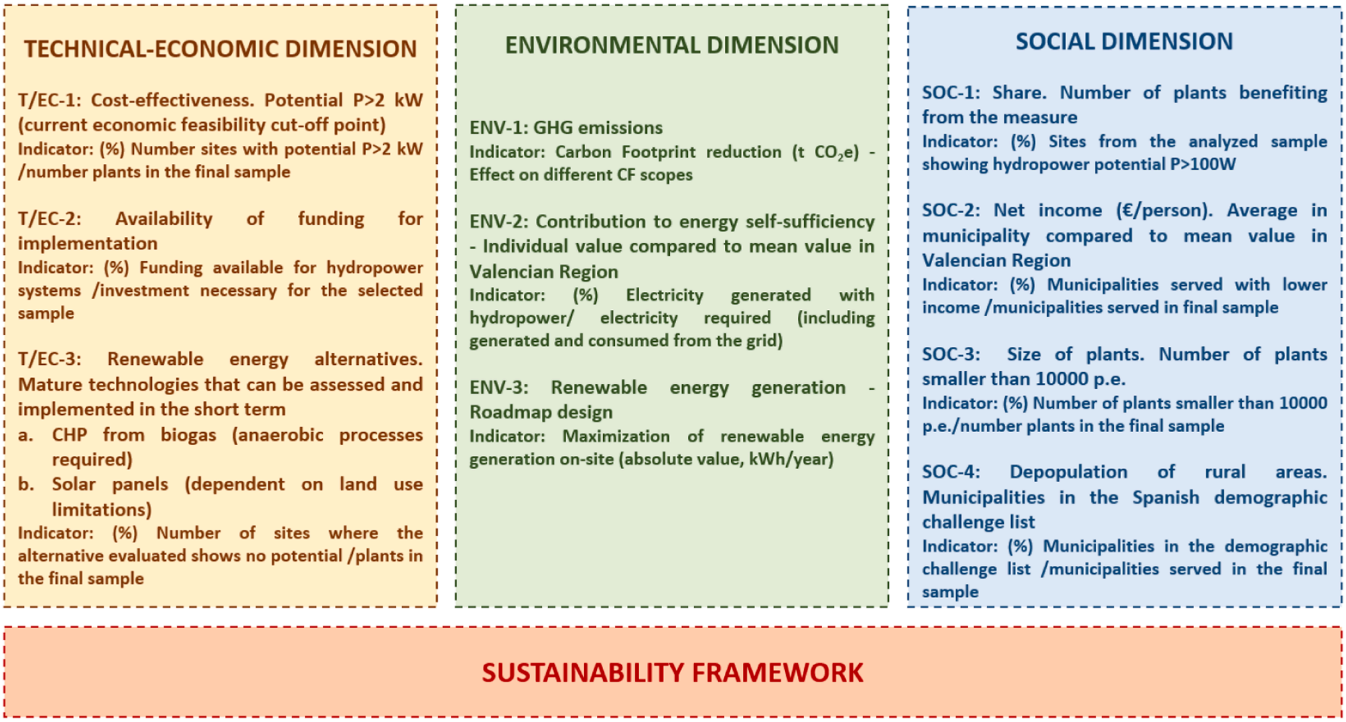


Fig. 5. Step 2. Process and outcomes in the determination of the global assessment for the selected sample.



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

Fig. 6. Proposed sustainability criteria for the case study.

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.

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. 79 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, as part of the sensitivity analysis.

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 4.2 (see Figs. 7, 8, and 9). Comparing the rankings for both scenarios, in most environmental (Fig. 8), and social (Fig. 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. 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.

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 4.2, 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. 11 shows the results of the effects of variations in the distribution of weights per dimension.

As shown in Fig. 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.

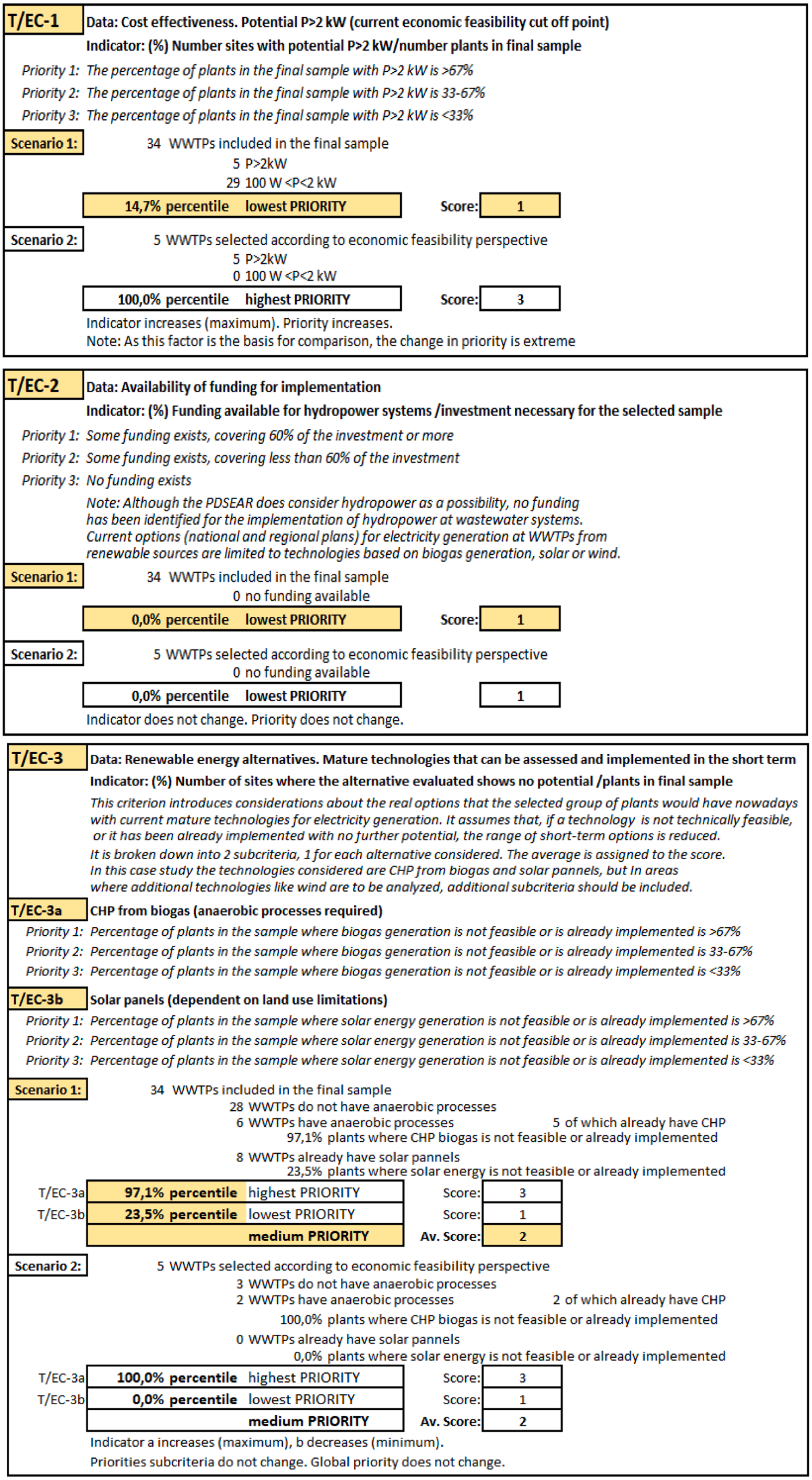
The effects of some possible changes in context, external or internal, are shown in Fig. 12. For example, if the market conditions change, and more affordable and cost-effective small-scale hydropower solutions were available, T/EC-1 might result in a higher score. Also might T/EC-2, if policies strengthen, 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.

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. 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



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

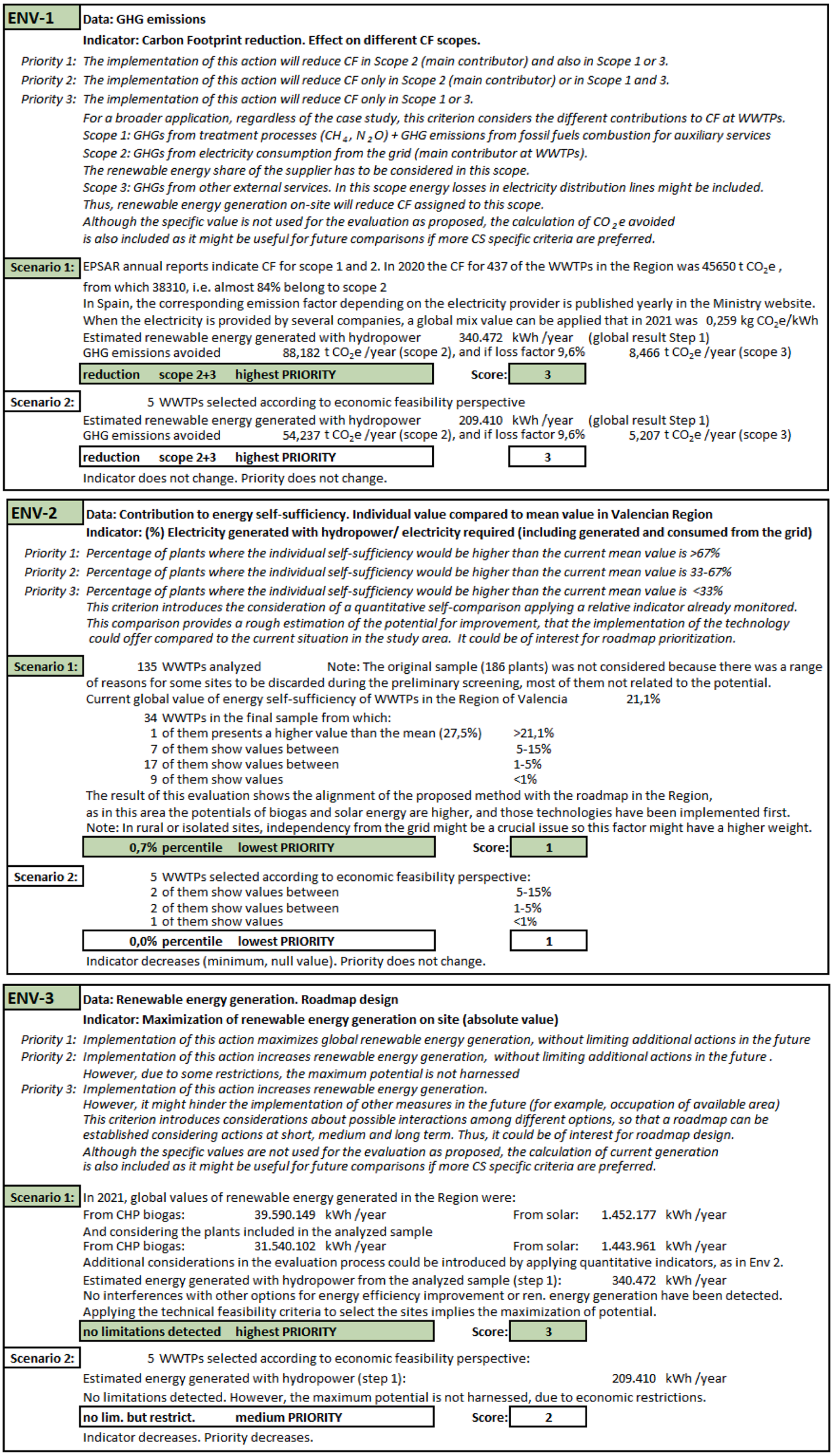
T/EC-3a	**97,1% percentile**	highest PRIORITY	Score:	3
T/EC-3b	**23,5% percentile**	lowest PRIORITY	Score:	1
		medium PRIORITY	**Av. Score:**	2

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.

Fig. 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.

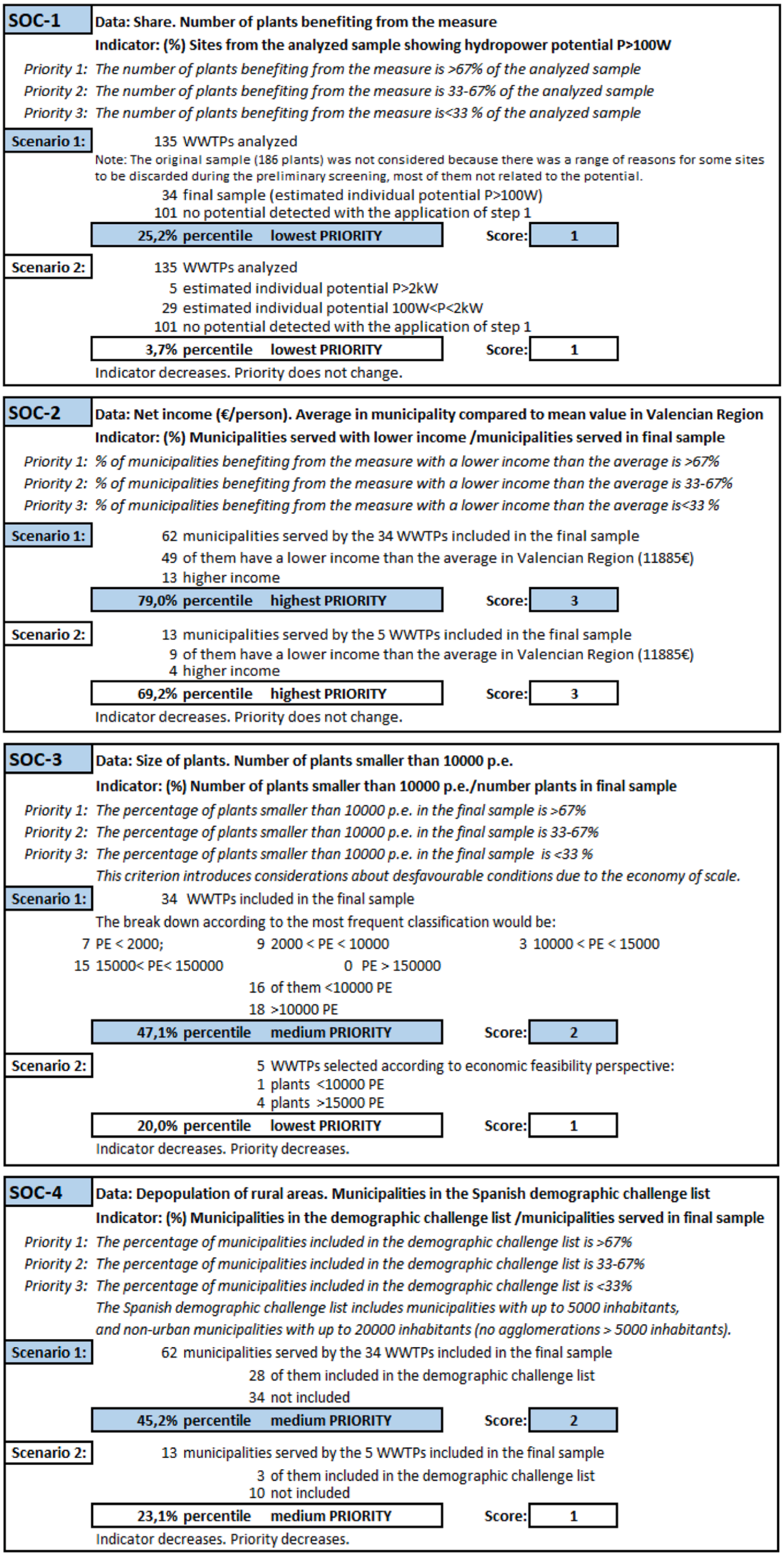
no limitations detected highest PRIORITY **Score: 3**

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.

Fig. 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

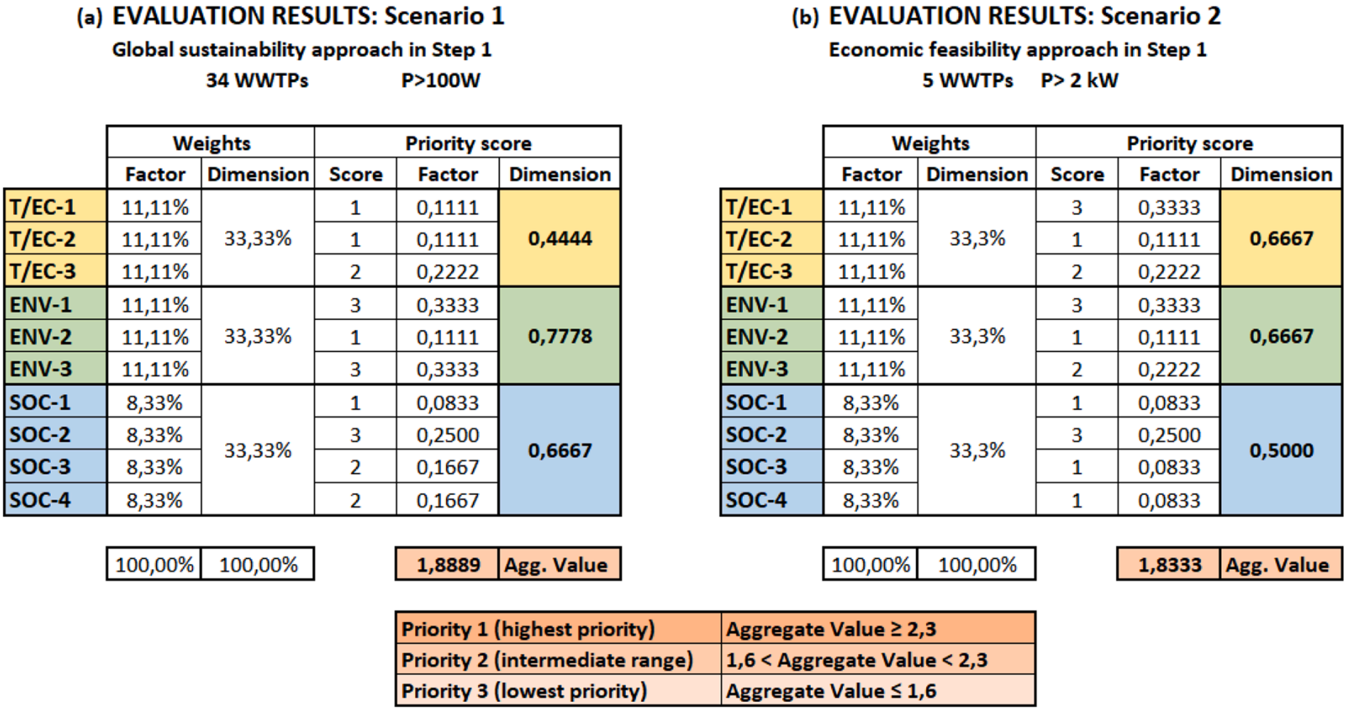
3 of them included in the demographic challenge list

10 not included

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

Indicator decreases. Priority decreases.

Fig. 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

Fig. 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 $P>2$ kW).

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.

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.

Data availability

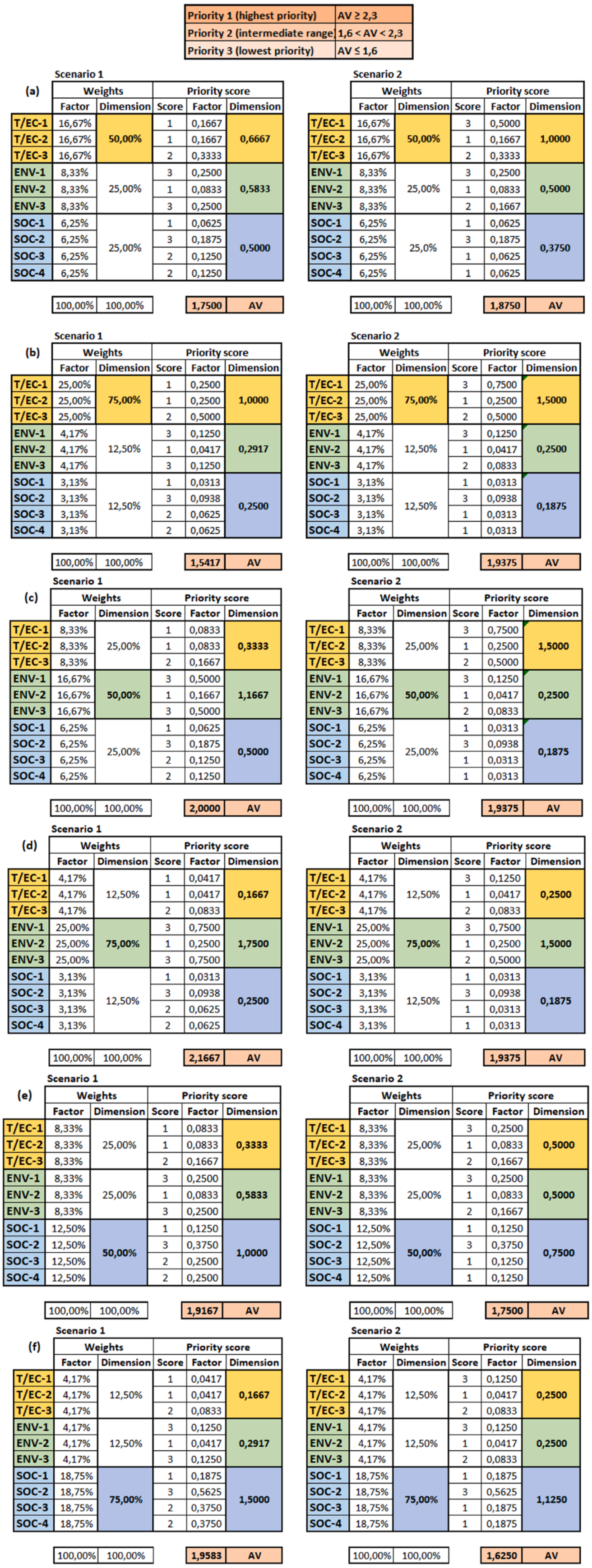
Data will be made available on request.

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.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.



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

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

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)

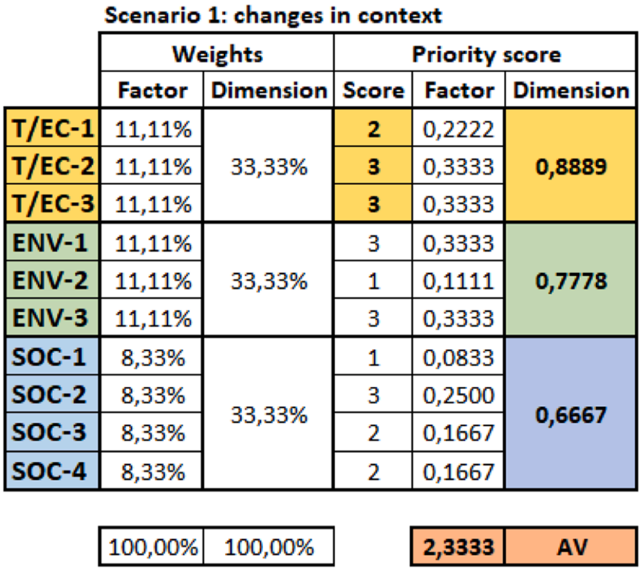
Scenario 1

	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

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

Fig. 11. Sensitivity analysis (Step 2). Effects of variations in the distribution of weights per dimension.



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

Fig. 12. Sensitivity analysis (Step 2). Effects of variations in the context on Scenario 1.

Data availability

Data will be made available on request.

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Supplementary materials

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

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