Collaborative elicitation to select a sustainable biogas desulfurization technique for landfills

ABSTRACT

The 2015 Paris Agreement within the United Nations Framework Convention on Climate Change establishes three key ways for the reduction of the emissions of Greenhouse Effect Gases: mitigation, adaptation and resilience of ecosystems. In this context, one of the major goals for methane recovery from waste is the process of obtaining biogas from biomass or waste, a form of fuel with zero impact on the carbon footprint of the planet. All possible uses of biogas depend mainly on the degree of purification obtained. The removal of hydrogen sulfide (H_2S) is the main weakness in using biogas in industrial applications. If the use of biogas is intended for engines, turbines or to enrich the biogas to obtain natural gas, lowering the levels of H_2S will be necessary, in order to avoid corrosion in gas lines and in engines. Biogas desulfurization can be achieved through different techniques: physical, chemical, biological or hybrid procedures. Selecting the most sustainable technique to clean biogas entails a complex problem, which involves the analysis of these desulfurization treatments under different criteria. In this paper, we present a novel collaborative elicitation to select the consensus procedure for the reduction of the concentration of H_2S in biogases from landfills. The elicitation technique is based on fuzzy set theory and VIKOR method in order to handle intangible data and to avoid potential bias by the panelists. The proposed hybrid method guarantees traceability and transparency to achieve consensus among the panel of experts during the decision making procedure.

KEYWORDS

Landfill biogas; desulfurization technique; collaborative elicitation; Fuzzy set; VIKOR method

1. Introduction

The Paris Agreement (2015) within the United Nations Framework Convention on Climate Change establishes three key ways for the reduction of the emissions of Greenhouse Effect Gases: mitigation, adaptation and resilience of ecosystems. They agreed on achieving climatic neutrality by mid-century. Therefore, emissions from electricity production, transport, industry, agriculture, deforestation and the use of natural resources must be absorbed by nature by this date. The Paris Agreement indicates as an energy related goal the increase in the proportion of renewable energy to levels from 79 to 81% in 2030. This is a challenging agenda for the implementation of sustainable models for growth and development. In this context, one of the major mechanisms for methane recovery from waste is the process of obtaining biogas from biomass or waste, a form of fuel with zero impact on the carbon footprint of the planet (Köcherman et al., 2015). Increasing this type of energy source is essential in order to reduce greenhouse effect gases (Moreno et al., 2017). The energy policy strategies of many countries give a high priority to renewable energy sources producing electricity, heat or biofuels (Cucchiella et al., 2014). To this end, many countries are implementing state strategies to increase biogas production from various sources of waste (Wang et al., 2018). The production of biogas is an environmentally sustainable activity, since it reduces the leaching of nutrients and the emissions of greenhouse gases in waste management (Ayodele et al., 2018). However, these fuel gases often contain concentrations of hydrogen sulfide (H_2S) of several hundred ppmv, and even thousands of ppmv, depending on the original residue (Cheah et al., 2009). The use of landfill gas requires high investment costs, both in gas cleaning and in its adaptation as an energy source (Chacartegui et al., 2015).

The purification of biogas for its injection into the natural gas network and its use as fuel for transport vehicles has a high growth potential (Osorio-Tejada et al., 2017). Most applications of synthesis gas involve the strict reduction of the levels of contaminants contained in the gas. This avoids important technical and environmental problems (Ryckebosch et al., 2015). The removal of H_2S is one of the crucial points for industries using biogas (Ozekmekci et al., 2015), as it is an extremely hazardous, corrosive and odorous gas (Liu et al., 2016). This concentration of H_2S must be reduced according to its final use (Abdoulmoumine et al., 2015). Nowadays, biogas plants combine together different physical and chemical treatments to achieve the required concentrations (Commission EU, 2016). Therefore, selecting the most sustainable hybrid procedure for stripping hydrogen sulfide implies a complex decision-making process. This paper proposes a method for achieving a compromise solution through the elicitation and ranking of desulfurization techniques under conflicting criteria via a panel of experts.

The fuzzy VIKOR method focuses on ranking and obtaining a compromise solution from a set of alternatives in a fuzzy environment (Opricovic, 2011). Whenever a panel of experts is required to solve complex problems with incommensurable variables, one of the major difficulties to overcome is the translation of the judgments from linguistic terms to numerical values. Fuzzy settings have been applied to solve this question in decision support systems (Sierra et al., 2018). The concept of fuzzy set was first proposed by Zadeh (1965) to deal with the uncertainty of human judgment preferences. The triangular fuzzy numbers, representing linguistic terms, are used to reflect the preferences of the panelists in the elicitation procedure to obtain the weights of the criteria and alternatives (Gul et al., 2016). The fuzzy algebra for ranking fuzzy numbers is applied to enhance the conventional VIKOR method (Wu et al., 2016a). The VIKOR method is an efficient tool used to handle conflicting and non-commensurable criteria in order to achieve a compromise solution (Opricovic, 1998). In the VIKOR method, the alternatives are evaluated according to the criteria selected. The final compromise solution ensures the maximum utility of the majority and the minimum individual regret (Opricovic and Tzeng, 2004). Assuming that the alternatives have been evaluated according to each criterion function, the compromise ranking can be performed by comparing the measure of closeness to the ideal alternative (Sayadi et al., 2009).

The VIKOR method has been successfully applied across different environmental areas. Cavallini et al. (2013) and Jahan and Edwards (2013) have used the VIKOR method to select materials in engineering design. Curiel-Esparza et al. (2014) have applied the VIKOR technique combined with Analytical Hierarchy Process (AHP) to elicit the best sustainable disinfection technique for wastewater reuse projects. Canto-Perello et al. (2015) have applied a multi-criteria hybrid model combining the AHP with the Delphi method and the VIKOR technique to implement sustainability criteria in the expert elicitation of a roof assembly in medium span buildings. Ren et al. (2015) have developed an illustrative case about three alternative bioethanol production scenarios (wheat-based, corn-based, and cassava-based). Tosic et al. (2015) have studied a VIKOR multi-criteria approach to integrate natural and recycled aggregate concrete for structural use. The VIKOR method has been used by Martin-Utrillas et al. (2015) in environmental engineering to select the best technique for purifying landfill leachate. A multi-criteria decision method technique, involving a fuzzy analytical hierarchy process integrated with techniques that order the preferences in terms of their similarities to the ideal solution and VIKOR techniques, has been employed by Anojkumar et al. (2015) for material selection in the sugar industry. A bridge model, based on a damaged bridge, has been subjected to nonlinear static pushover analyses performed by Cosic et al. (2016) with the VIKOR method. Wu et al. (2016b) have applied the VIKOR method using linguistic information in the selection of suppliers in the nuclear power industry. Curiel-Esparza et al. (2016) have used the VIKOR method to analyze sustainable mobility in urban areas. Soner et al (2017) have employed method using fuzzy environments in the analysis of maritime transportation.

In this paper, we propose a novel hybrid collaborative elicitation combining the fuzzy sets with the VIKOR method to select the most sustainable desulfurization technique for landfill biogas. This hybrid procedure reaches consensus among all the panelists sharing different points of view in solving a complex situation. In addition, one of the outcomes of this collaborative elicitation technique is to avoid the biases found in individual elicitation. The proposed structured framework integrating operation, maintenance and efficiency indicators helps achieving the final consensus. The main strength is the ability to deal with intangible criteria using fuzzy triangular numbers. Moreover, the achieved desulfurization procedure must also verify the conditions of acceptable advantage and stability to ensure the maximum group utility and the minimum individual reject.

2. Collaborative elicitation and method

2.1. Study location and panelists

The proposed framework has been applied to a landfill located in the city of Villena, in the region of Alicante (Spain). It occupies a land surface area of 0.90 square kilometers and it is a landfill for non-hazardous industrial waste. The landfill receives more than 130,000 tons of waste each year. This waste cannot be subjected to recovery processes. From a geological point of view, the landfill is located in Triassic formations rich in gypsum, clays and marls, allowing the land to be suitable and safe for the installation of controlled landfills, independently of the necessary waterproofing. The gas generated has a high H_2S content, with a mean value of 20,000 ppmv. The framework is based on the judgements of a panel of experts on the underlying problem and provides aggregated results. There is discussion on what the number of experts in the panel should be. To ensure the strength of the solution achieved, at least six panelists should be interviewed. The benefit of including an additional panelist begins to decrease from twelve panelists (Cooke and Probst, 2006). Novakowski and Wellar (2008) have stated that a panel size of eight to twelve members should be appropriate in most cases, and sufficient when developing appropriate judgements through consensus as in our case. More specifically, Alvarez et al. (2015) have also advised a panel size between eight and twelve experts when anonymous individual responses from the panelists are used as in our framework. In addition, H_2S removal is a technically complex process, so the panel components must be qualified experts with in-depth knowledge of the target of the study (Okoli and Pawlowski, 2004). Consequently, the collaborative framework has relied on a panel of experts, and not stakeholders that could be non-expert. The panelists involved in this study are composed of twelve environmental and chemical engineers. All of them are Spanish nationals, with extensive professional experience. It is intended for the experts to not confront each other. On the contrary, we act in this way to try to study the convergence of points of view on the question posed.

2.2. Decision hierarchy structure for energy valorization of biogas

The aim of this method is to gather not only the raw opinions of experts on a certain number of questions concerning different future scenarios but also to make each expert react to the general opinions of his or her peers. The first phase will be the exploration of the alternatives and the criteria under discussion between experts (Canto-Perello et al., 2018). To do this, an anonymous questionnaire was sent out in two successive mailings. The second mailing was adjusted according to the findings of the first one. The use of mailing allows identifying the convergence of opinion between experts by specifically avoiding all potential source of discord or conflict. Criteria and alternatives that are accorded low importance are removed. The goal has been structured according to the three level hierarchical framework shown in Fig. 1. The intermediate level shows the criteria selected by the panelists taking into account the specific characteristics of the biogas along with the best available technologies and sustainable strategies. These criteria are operational economic issues (OECI); flexibility in the inlet flow (FLEX); foam formation (FOAM); efficiency (EFFC); residence times (REST), and secondary contaminants (SECC). Finally, in the lower level, the panelists have evaluated the following technical alternatives for H_2S removal:

- Equipment for the removal of H_2S by biological means (BIOM). Biological means are carried out by the action of certain microorganisms such as sulfur-oxidizing bacteria, which convert H_2S to elemental sulfur or metal sulfides. Many microorganisms are known to inhabit humid places and are consumers of H_2S as a nutritional source, covering their surroundings with elemental sulfur. These have a preference for wastewater and never stop growing and multiplying while environmental conditions allow them to. They can live both in the presence and absence of oxygen, although there are certain factors that favor their growth and development such as: moisture, presence of oxygen, existence of H_2S and residual liquid as a bacterial transporter. Among the products that can be used as essential parts of the biological filter is the use of algae (micro or macro) (Muñoz et al., 2015).

- H_2S chemical removal equipment (CHEM). This method is based on the transfer of mass between the gaseous substance to be purified and a liquid, called absorber, which has selective absorption properties. The most common solvent is water. In the shower column (scrubber), carbonate solutions (potassium or sodium carbonate) are used to reduce hydrogen sulfide. Scrubbing systems additionally use increased pressure to improve the system's efficiency. Aqueous alkaline solutions have also been employed. Their main advantage is that the lack of corrosion problems and foaming make scrubbing less expensive. However, the anti-foam agent makes the equipment and operation more complex. This method presents a high-energy consumption because of the pumping of the solution and of the gases (Miltner et al., 2012).
- Equipment for the removal of H_2S by adsorption (active carbon) (ADSP). This method is one of the most widely used procedures to remove H_2S from landfill gas when low concentrations are required (Köchermann et al., 2015). In addition to the physical adsorption, activated carbon significantly improves the H_2S removal capacity, as it provides a large catalytic surface for oxidation to elemental sulfur and sulfate (Nam et al., 2018). Activated carbon has been produced from sewage sludge as a low cost adsorbent, as well as other natural materials, like agricultural, industrial or domestic waste. Some of its by-products have also been used, such as sludge, fly ash, slag or bagasse.
- Addition of reagents in the biodigester (BIOD). By adding liquid mixtures of various metal salts (e.g. ferric chloride or ferric sulfate) to the digester (as well as to the maceration tank before the digester) a precipitation of the sulfur content in the substrate is achieved. Sulfur is made from almost insoluble iron inside the biogas fermenter. Iron sulfide is removed through fermentation along with the digestate. Oxygen is sometimes injected into the gas stream to allow partial regeneration of the reaction vessel. This is a very effective method to reduce the high levels of H_2S, but its effectiveness is lower when trying to achieve a low and stable level of H_2S for injection in gas networks. Reductions of H_2S concentrations in the biogas of up to 200 - 100 ppm have been achieved (Bailon and Hinge, 2014). If the intention is to reach lower concentrations, the process will require a large excess of iron ions. This technology allows the elimination of other pollutants from biogas, such as ammonia (Environment Agency Wales, 2010).
- Equipment for the removal of H_2S by means of a physical route using membranes (PHRM). This process is based on the diffusion of some compounds that pass through a selective membrane. In order to facilitate the diffusion, a carrier is used. The permeability of the gas through the membrane is a function of the solubility and diffusivity of the gas in the material of the membrane (Burke et al., 2002). It allows the separation of different gases depending on the membrane, such as CO_2, H_2S, H_2 and other hydrocarbons and light gases. Different membrane filters have been tested for the separation of hydrogen sulfide and CO_2 from the gas (Zhang et al., 2017). The equipment and the operation of this method are simple. However, the efficiency of the membrane separation is low and its cost is high. In addition, the application of high pressures is necessary.
- Equipment for the removal of H_2S through a chemical -biological route (CBIR). The system consists of two reactors. The first one is an absorption tower, where the contaminants are absorbed in a liquid phase, which then goes to the second reactor. This second reactor is an activated sludge unit, where microorganisms grow in flocks suspended in water and degrade contaminants. The effluent from this unit is recirculated onto the absorption tower. The process integrates gas purification with the recovery of sulfur in a single unit, using bacteria of a natural origin, which oxidize H_2S to elemental sulfur. The gas with H_2S first comes into contact with the poor solution in the absorber, where it absorbs H_2S, forming sodium sulfides (Ho et al., 2013). The purified gas exits the absorber, ready for use or later processing. The sulfide-loaded solution is directed to a flash evaporation vessel or to a bioreactor, operating

at atmospheric pressure and room temperature. In the bioreactor, the microorganisms oxidize the sulfur, turning it into elemental sulfur. This elemental sulfur is then separated from the water by means of a centrifugal decanter. Water is reused in the process. It is necessary to continuously monitor the addition of nutrients, oxygen and control pH levels to maintain microbial growth and high activity. The biomass excess and by-products are continuously purged from the system.

2.3. Fuzzy analysis of the criteria and desulfurization techniques

Fuzzy linguistic variables allow decision makers to express their judgements and preferences (Zadeh, 1975). To reach the goal, the weights of the criteria and alternatives have been analyzed through linguistic variables, which are expressed using triangular fuzzy numbers. In addition, Zadeh (2015) stated three main reasons for the use of precise words instead of numbers. First, the use of words, accurate or not, is a necessity when there are no numerical values for the variables. The second reason applies to when there is a tolerance for imprecision. The replacement of numbers with precise words can be seen as a formalization of an important aspect of the human behavior. The third reason has to do with what Zadeh (2015) called ‘cointensive indefinability’. By applying the precise words, a fuzzy concept can be defined mathematically. Triangular fuzzy numbers have been used to represent these linguistic terms. The triangular fuzzy linguistic variables for the evaluation of the criteria importance weights and for the rating of the six alternatives under the six criteria are shown in Table 1 and Fig. 2. 3. The same linguistic scale is used when ranking criteria and alternatives under criteria in order to facilitate the panelists' judgments.

Table 1
Linguistic terms description with triangular fuzzy numbers

Abbreviation	Description	Fuzzy value
EXN	Extremely non-preferred criterion or technique over others	(0, 0, 0.167)
VSN	Very strongly non-preferred criterion or technique over others	(0, 0.167, 0.333)
SLN	Slightly non-preferred criterion or technique over others	(0.167, 0.333, 0.500)
EQP	Equally preferred criterion or technique over others	(0.333, 0.500, 0.667)
SLP	Slightly preferred criterion or technique over others	(0.500, 0.667, 0.833)
VSP	Very strongly preferred criterion or technique over others	(0.667, 0.833, 1)
EXP	Extremely preferred criterion or technique over others	(0.833, 1, 1)

Decision makers have provided their fuzzy weights for the criteria and the fuzzy analysis for each desulfurization technique. The evaluations of the criteria are given in Appendix 1, and the analyses of the desulfurization techniques under each criterion are shown in Appendix 2.

2.4. Aggregation of individual elicitation judgements

The individual elicitation judgments are aggregated to obtain the group preferences. These individual elicitation judgments are inherently biased. However, any bias in individual judgements has a small influence on the achieved solution if it is reached through group consensus (Sebok et al 2016, Canto-Perello et al 2017). As a first step in the elicitation procedure, the linguistic variables are assigned to triangular fuzzy numbers according to the membership functions shown in Table 1. The fuzzy weights of each criterion are obtained by applying the triangular fuzzy average formula. In the case of the FOAM criterion, with twelve decision makers, the formula is:

$$\widetilde{FOAM} = \frac{1}{12} \sum_{i=1}^{12} \oplus \widetilde{FOAM}_i \quad (1)$$

where $\widetilde{FOAM}_i$ is the judgement of each expert (i= 1, 2, …, 12) for the FOAM criterion expressed in fuzzy terms $(l_i^{FOAM}, m_i^{FOAM}, u_i^{FOAM})$. The collaborative elicitation of fuzzy weights $\widetilde{w}_j$ of each criterion is shown in Table 2.

Table 2
Collaborative elicitation fuzzy weights $\widetilde{w}_j$ of the criteria

	l	m	u
$\widetilde{OECI}$	0.7483	0.9167	0.9717
$\widetilde{FLEX}$	0.6375	0.8058	0.9025
$\widetilde{FOAM}$	0.3750	0.5400	0.7100
$\widetilde{EFFC}$	0.2217	0.3883	0.5567
$\widetilde{REST}$	0.2492	0.4033	0.5700
$\widetilde{SECC}$	0.2375	0.3600	0.5283

Analogously, the collaborative elicitation of the fuzzy number for each desulfurization technique under each criterion is computed as shown in Table 3.

Table 3
Collaborative elicitation fuzzy number of each desulfurization technique under each criterion

Desulfurization Technique	OECI			FLEX			FOAM		
	l	m	u	l	m	u	l	m	u
$\widetilde{BIOM}$	0.0842	0.2225	0.3883	0.1817	0.3467	0.5133	0.5542	0.7233	0.8467
$\widetilde{CHEM}$	0.2908	0.4575	0.6125	0.6400	0.8033	0.9308	0.5133	0.6667	0.7917
$\widetilde{ADSP}$	0.3608	0.5275	0.6808	0.6108	0.7775	0.8883	0.6242	0.7917	0.9025
$\widetilde{BIOD}$	0.3750	0.5300	0.6925	0.3050	0.4725	0.6250	0.1658	0.2792	0.4450
$\widetilde{PHRM}$	0.3617	0.5267	0.6808	0.6525	0.8183	0.9308	0.5133	0.6383	0.7367
$\widetilde{CBIR}$	0.6542	0.8175	0.9442	0.7075	0.8742	0.9583	0.7492	0.9158	0.9858
Desulfurization Technique	**EFFC**			**REST**			**SECC**		
	l	**m**	**u**	**l**	**m**	**u**	**l**	**m**	**u**
$\widetilde{BIOM}$	0.2500	0.4167	0.5833	0.4725	0.6392	0.7767	0.3733	0.5425	0.7092
$\widetilde{CHEM}$	0.0425	0.1675	0.3325	0.4592	0.6250	0.7908	0.5283	0.6950	0.8600
$\widetilde{ADSP}$	0.4592	0.6108	0.7633	0.5558	0.7225	0.8600	0.4867	0.6525	0.8192
$\widetilde{BIOD}$	0.3750	0.5425	0.6933	0.3458	0.5008	0.6533	0.5275	0.6942	0.8333
$\widetilde{PHRM}$	0.6533	0.8175	0.9167	0.6108	0.7625	0.8617	0.7225	0.8875	0.9858
$\widetilde{CBIR}$	0.7492	0.9158	0.9858	0.6533	0.8183	0.9300	0.6950	0.8600	0.9717

Combining the data in Table 2 and Table 3, the aggregated fuzzy number decision matrix is obtained (see Table 4).

Table 4
Collaborative elicitation fuzzy number decision matrix

		BIOM	CHEM	ADSP	BIOD	PHRM	CBIR
OECI	l	0.0842	0.2908	0.3608	0.3750	0.3617	0.6542
	m	0.2225	0.4575	0.5275	0.5300	0.5267	0.8175
	u	0.3883	0.6125	0.6808	0.6925	0.6808	0.9442
FLEX	l	0.1817	0.6400	0.6108	0.3050	0.6525	0.7075
	m	0.3467	0.8033	0.7775	0.4725	0.8183	0.8742
	u	0.5133	0.9308	0.8883	0.6250	0.9308	0.9583
FOAM	l	0.5542	0.5133	0.6242	0.1658	0.5133	0.7492

	m	0.7233	0.6667	0.7917	0.2792	0.6383	0.9158
	u	0.8467	0.7917	0.9025	0.4450	0.7367	0.9858
EFFC	**l**	0.2500	0.0425	0.4592	0.3750	0.6533	0.7492
	m	0.4167	0.1675	0.6108	0.5425	0.8175	0.9158
	u	0.5833	0.3325	0.7633	0.6933	0.9167	0.9858
REST	**l**	0.4725	0.4592	0.5558	0.3458	0.6108	0.6533
	m	0.6392	0.6250	0.7225	0.5008	0.7625	0.8183
	u	0.7767	0.7908	0.8600	0.6533	0.8617	0.9300
SECC	**l**	0.3733	0.5283	0.4867	0.5275	0.7225	0.6950
	m	0.5425	0.6950	0.6525	0.6942	0.8875	0.8600
	u	0.7092	0.8600	0.8192	0.8333	0.9858	0.9717

3. Results

3.1. Achieving the compromise desulfurization technique by consensus

The best compromise solution is determined from the set of six feasible techniques evaluated according to the set of six criterion functions by the triangular fuzzy numbers $\widetilde{f_{ij}} = (l_{ij}, m_{ij}, u_{ij})$, where i = 1, 2, …, 6 and j = 1, 2, …, 6. The input data are the elements of the performance decision matrix, where f_{ij} is the value of the i^{th} criterion function for each j^{th} technique. The fuzzy VIKOR procedure is applied as follows:

Firstly, the best $\tilde{f}_j^*$ and the worst $\tilde{f}_j^-$ fuzzy values for all criteria ratings *j* = 1, 2, …, 6 are computed.

$$\tilde{f}_j^* = max_i\{\tilde{f}_{ij}\} \quad (2)$$

$$\tilde{f}_j^- = min_i\{\tilde{f}_{ij}\} \quad (3)$$

and the results are shown in Appendix 3.

The fuzzy differences $\tilde{d}_{ij}$, where i = 1, 2, …, 6 and j = 1, 2, …, 6, are computed with the formula (4), and the results are showed in Appendix 4.

$$\tilde{d}_{ij} = \frac{\tilde{f}_j^* \ominus \tilde{f}_{ij}}{u_j^* - l_j^-} \quad (4)$$

Fuzzy differences are then combined with the criteria's fuzzy weighting matrix (see Table 2) to obtain the normalized fuzzy differences matrix (see Table 5).

Table 5
Normalized fuzzy differences $\tilde{d}_{ij}$

Criteria		BIOM	CHEM	ADSP	BIOD	PHRM	CBIR
OECI	**l**	0.2313	0.0363	-0.0232	-0.0334	-0.0232	-0.2523
	m	0.6342	0.3837	0.3091	0.3064	0.3100	0.0000
	u	0.9717	0.7382	0.6591	0.6431	0.6581	0.3277
FLEX	**l**	0.1594	-0.1833	-0.1484	0.0677	-0.1833	-0.2059
	m	0.5473	0.0735	0.1003	0.4168	0.0579	0.0000
	u	0.9025	0.3699	0.4038	0.7592	0.3554	0.2915
FOAM	**l**	-0.0446	-0.0194	-0.0701	0.1391	0.0057	-0.1082
	m	0.1268	0.1641	0.0818	0.4193	0.1827	0.0000

	u	0.3738	0.4091	0.3132	0.7100	0.4091	0.2049
	l	0.0390	0.0979	-0.0033	0.0131	-0.0394	-0.0556
EFFC	**m**	0.2055	0.3081	0.1256	0.1537	0.0405	0.0000
	u	0.4342	0.5567	0.3108	0.3605	0.1962	0.1397
	l	-0.0526	-0.0586	-0.0882	0.0000	-0.0889	-0.1180
REST	**m**	0.1237	0.1335	0.0662	0.2192	0.0385	0.0000
	u	0.4464	0.4594	0.3651	0.5700	0.3114	0.2700
	l	0.0052	-0.0533	-0.0375	-0.0430	-0.1021	-0.0966
SECC	**m**	0.2028	0.1131	0.1381	0.1136	0.0000	0.0162
	u	0.5283	0.3946	0.4306	0.3954	0.2271	0.2509

3.2. Ranking and fulfillment of conditions

VIKOR is an effective technique to solve discrete decision problems when the panelists are not able to express their judgments at the early stages (Gupta et al., 2016). The method ranks the desulfurization procedures according to the value of three fuzzy indicators ($\tilde{S}_i$, $\tilde{R}_i$, and $\tilde{Q}_i$) to be computed for each technique. The minimum $\tilde{S}_i$ fuzzy number indicates the maximum utility for the majority, while the $\tilde{R}_i$ fuzzy indicator provides the minimum individual regret for the opponent. The indicators $\tilde{S}_i$ and $\tilde{R}_i$ are combined to compute the $\tilde{Q}_i$ fuzzy indicator in order to achieve the compromise desulfurization technique and to guarantee consensus. Finally, the two requirements of acceptable advantage and stability must be verified to ensure the decision making procedure. The fuzzy indicators $\tilde{S}_i$and $\tilde{R}_i$ are computed using the equations (5) and (6), as follows:

$$\tilde{S}_i = \sum_{j=1}^{n} \otimes \tilde{w}_j \otimes \frac{\tilde{f}_j^* \ominus \tilde{f}_{ij}}{u_j^* - l_j^-} \quad (5)$$

$$\tilde{R}_i = max_j \tilde{w}_j \otimes \frac{\tilde{f}_j^* \ominus \tilde{f}_{ij}}{u_j^* - l_j^-} \quad (6)$$

The fuzzy indicator $\tilde{Q}_i = \left(Q_i^l, Q_i^m, Q_i^u\right)$ is computed applying the equation (7):

$$\tilde{Q}_i = \gamma \frac{\tilde{S}_i \ominus \tilde{S}_{min}}{S_{max}^u - S_{min}^l} \oplus (1-\gamma) \frac{\tilde{R}_i \ominus \tilde{R}_{min}}{R_{max}^u - R_{min}^l} \quad (7)$$

where

$\tilde{S}_{min} = min_i \tilde{S}_i$ $\qquad$ $\tilde{R}_{min} = min_i \tilde{R}_i$

$S_{max}^u = max_i S_i^u$ $\qquad$ $R_{max}^u = max_i R_i^u$

$S_{min}^l = min_i S_i^l$ $\qquad$ $R_{min}^l = min_i R_i^l$

and γ is the weight for the strategy of maximum group utility and (1-γ) is the weight of the individual reject. Its value is 0.5 when a consensus strategy is required, as is this case. Appendix 5 shows the $\tilde{S}_i$, $\tilde{R}_i$ and $\tilde{Q}_i$ fuzzy indicators for all the analyzed desulfurization techniques applying the equations (5), (6) and (7), with γ = 0.5. The minimum and maximum values of S and R are marked in the table of Appendix 5 in bold letters and their values are:

S_l min = -0.8367 $\qquad$ R_l min = -0.0556 $\qquad$ corresponding to $\tilde{S}_6$ and $\tilde{R}_6$ (CBIR).

S_u max = 3.6569 $\qquad$ R_u max = 0.9717 $\qquad$ corresponding to $\tilde{S}_1$ and $\tilde{R}_1$ (BIOM).

The fuzzy indicators $\tilde{S}_i, \tilde{R}_i$ and $\tilde{Q}_i$, are defuzzified using the centroid method algorithm to crisp numbers S_i, R_i and Q_i, as shown in formula (8).

$$S_i = \frac{S_i^l + S_i^m + S_i^u}{3},\ R_i = \frac{R_i^l + R_i^m + R_i^u}{3},\ Q_i = \frac{Q_i^l + Q_i^m + Q_i^u}{3}, \qquad (8)$$

The crisp values are presented in Appendix 6. The minimum and maximum values of S, R and Q are:

Crisp min (S) = 0.2213, corresponding to the CBIR technique.

Crisp min (R) = 0.0961, corresponding to the CBIR technique.

Crisp max (Q) = 0.4431, corresponding to the BIOM technique.

In order to achieve the compromise desulfurization technique, the techniques have been sorted according to the values *S, R* and *Q* in ascending order as shown in Table 6.

Table 6
Ranking of desulfurization techniques

	BIOM	**CHEM**	**ADSP**	**BIOD**	**PHRM**	**CBIR**
By Si Crisp	6	4	3	5	2	1
By Ri Crisp	6	4	2	5	3	1
By Qi Crisp	6	4	3	5	2	1
Position	**1**	**2**	**3**	**4**	**5**	**6**
By Si Crisp	CBIR	PHRM	ADSP	CHEM	BIOD	BIOM
By Ri Crisp	CBIR	ADSP	PHRM	CHEM	BIOD	BIOM
By Qi Crisp	CBIR	PHRM	ADSP	CHEM	BIOD	BIOM

It can be seen from the results of Table 6, that the chemical and biological route (CBIR) is the best technique by the Q_i value ranking (minimum). This first technique ($CBIR^{(1)}$) would be proposed as a compromise solution if the following two conditions are satisfied:

Condition 1: Acceptable advantage (Adv).

$$Adv = \frac{Q(PHRM^{(2)}) - Q(CBIR^{(1)})}{Q(BIOM^{(6)}) - Q(CBIR^{(1)})} > DQ \qquad (9)$$

Where $PHRM^{(2)}$ is the technique ranked in second position in the ranking list by Q, $BIOM^{(6)}$ is the technique ranked in last position in the ranking list by Q, while, DQ = 1/(J-1), being J the number of desulfurization techniques considered, 6 in this case. Substituting in formula (9), the value of Adv is obtained:

$Adv = \frac{0.1740-0}{0.4431-0} = 0.3927 > DQ = 0.200$ so the acceptable advantage condition C1 is satisfied.

Condition 2: Acceptable stability in decision making.

The $CBIR^{(1)}$ technique must also have the best ranking by S and/or R in order to reach the compromise solution. The acceptable stability condition is satisfied, because the best desulfurization technique for Q, chemical-biological route (CBIR), is also the best ranked by S and R (considering the 'by consensus rule γ ≈ 0.5'), and it is finally chosen and ranked as the best technique for a desulfurization process of biogas.

If one of the conditions is not satisfied, then a set of compromise solutions would be proposed, which would consist of:

- Technique *CBIR*(1) and *PHRM*(2) if only the condition C2 is not satisfied, or
- Technique *CBIR*(1), *PHRM*(2),., *BIOM*(6) if the condition C1 is not satisfied. In this case the position of these techniques would be 'in closeness'.

According to the VIKOR method, the obtained compromise solution would be accepted by the decision makers because it provides a maximum utility of the majority (represented by min S), and a minimum individual regret of the opponent (represented by min R). In addition, parameters S and R have been integrated into parameter Q in order to obtain this compromise solution.

4. Discussion

In order to comply with the environmental objectives of the Paris Summit, the use of biogas as a fuel is highly recommended as one of the different strategies to reduce the greenhouse gases emissions. This increases the proportion of renewable energy in the energy generation mix. Therefore, biogas represents one of the energy resources with the greatest growth potential in the world. However, biogas contains certain concentrations of H_2S and other undesirable compounds which needs to be purged for energy use. H_2S is one of the most problematic contaminants when using digester gas or degassing as an energy source, as it is toxic and corrosive for most of the equipment, as well as being an odorous compound. There are many techniques to reduce or eliminate H_2S from the syngas, which can be used alone or combined. An incorrect selection could cause a great environmental and economic damage to companies that have to implement the use of biogas as fuel. In this context, the desulfurization technique's selection raises a multiple-criteria decision-making problem. The VIKOR method has been applied to address this problem with conflicting criteria and to assist the expert panelists. The translation of the panelists' judgments in terms of mathematical language is one of the key issues in complex problems with incommensurable variables. In order to solve this issue, the VIKOR method has been developed using a fuzzy environment. Diffuse operations and procedures for the classification of fuzzy numbers have been applied throughout the fuzzy VIKOR algorithm. The proposed collaborative elicitation allows the panelists to express their preferences about criteria and alternatives in linguistic terms, which are then transformed into numbers that can be integrated into numerical equations. Furthermore, the data obtained from the panel of experts are the best guarantee that the result of the decision is more reliable than when it is made by a single expert.

5. Conclusions

The most important criteria have been operational economic issues (OECI), flexibility of the installation contrasted to the variations of inlet flow (FLEX) and the formation of foams in the cleaning process (FOAM). On the other hand, the criterion with lower priority in the selection of desulfurization treatments has been SECC, which is related to the secondary contaminants obtained in the processes. The preferred technique for the desulfurization of the landfill gases consists of a mixed treatment by means of a chemical and biological route (CBIR). This technique has approached the ideal solution in nearly all of the criteria analyzed, which can be observed in Fig. 3, and therefore, it has been the best ranked by the panelists. Only the desulfurization technique applying a physical route using membranes (PHRM) has been better ranked in the least valued criterion, secondary contaminants (SECC). Chemical elimination equipment (CHEM), biological means equipment (BIOM) and addition of reagents in the biodigester (BIOD) have been ranked away from the ideal solution chosen by the experts in almost all of the analyzed criteria. By studying the graph in Fig. 3, it can be observed that the residence time (REST) and flexibility with the inlet flow (FLEX) criteria yield homogeneous results in all of the treatments. This is not the case with the foam formation (FOAM) and operation economic issues (OECI) criteria.

Under these criteria, BIOD (addition of reagents in the biodigester) and BIOM (biological means) treatments are far from the rest of the desulfurization methods.

The conclusions of the proposed method have been achieved based on the judgements of a panel of experts. The procedure ensures an equal treatment for every panelist with traceability and transparency to reach the necessary consensus. The anonymous open-ended questionnaires from the experts have allowed the designing of the hierarchical structure of the criteria and technical alternatives of gas cleaning, among the many possibilities that exist in the market. Experts have also prioritized among the criteria used. As shown, the fuzzy VIKOR method has reached a stable solution with commitment among the consulted panelists for selecting the best desulfurization technique in landfill biogas treatment.

Appendix 1. Individual elicitation of each criterion using linguistic terms

Decision makers	OECI	FLEX	FOAM	EFFC	REST	SECC
D1	EXP	SLP	EQP	EQP	VSN	EXN
D2	EXP	EQP	VSP	EQP	EQP	SLN
D3	SLP	EXP	EQP	VSN	EQP	VSN
D4	EXP	VSP	SLN	SLN	VSP	VSP
D5	SLP	SLP	SLN	SLN	SLN	VSP
D6	EXP	EXP	EQP	EQP	VSN	EQP
D7	EXP	EXP	VSP	EQP	EXN	EXN
D8	EXP	VSP	EQP	VSN	SLP	VSP
D9	VSP	EXP	EQP	EQP	VSN	EXN
D10	VSP	SLP	SLN	EQP	EQP	VSN
D11	EXP	EXP	VSP	SLN	EQP	SLN
D12	EXP	EQP	EQP	SLN	EQP	SLN

Appendix 2. Individual elicitation of the desulfurization techniques under each criterion

Decision makers	Desulfurization Technique	Criteria					
		OECI	FLEX	FOAM	EFFC	REST	SECC
D1	BIOM	EXN	EQP	EQP	VSN	EXP	SLP
	CHEM	EQP	EXP	EXP	VSN	VSP	SLP
	ADSP	VSN	EXP	EXP	EXP	VSP	VSP
	BIOD	SLP	VSN	VSN	VSN	SLN	VSP
	PHRM	VSN	VSP	VSP	EXP	EXP	EXP
	CBIR	EXP	EXP	EXP	EXP	VSP	VSP
D2	BIOM	VSN	SLN	SLP	SLN	SLP	SLP
	CHEM	EQP	VSP	EXP	EXN	VSP	EQP
	ADSP	SLN	VSP	VSP	VSP	EQP	SLP
	BIOD	VSP	SLN	VSN	EQP	EQP	EQP
	PHRM	SLN	EXP	EXP	VSP	EXP	EXP
	CBIR	EXP	VSP	VSP	VSP	EXP	VSP
D3	BIOM	VSN	SLN	EQP	SLN	EXP	EQP
	CHEM	EQP	EXP	EQP	VSN	SLP	VSP
	ADSP	SLP	SLP	SLP	VSP	SLP	SLP
	BIOD	VSN	SLN	EXN	SLN	EQP	SLP

	PHRM	SLN	VSP	EXP	VSP	VSP	VSP
	CBIR	VSP	EXP	VSP	EXP	VSP	SLP
D4	**BIOM**	EXN	SLN	EXP	VSN	VSP	SLN
	CHEM	EQP	VSP	VSP	VSN	VSP	SLP
	ADSP	SLN	EXP	VSP	VSP	EXP	VSP
	BIOD	SLP	EXP	EXN	SLP	EQP	EQP
	PHRM	SLN	EXP	EXP	VSP	VSP	SLP
	CBIR	VSP	VSP	EXP	EXP	EXP	VSP
D5	**BIOM**	VSN	SLN	SLP	VSN	VSP	EQP
	CHEM	SLN	VSP	SLP	EXN	SLP	VSP
	ADSP	SLN	EXP	EXP	VSP	EXP	VSP
	BIOD	SLP	SLN	VSN	SLN	VSN	VSP
	PHRM	SLN	EXP	EXP	EXP	EXP	EXP
	CBIR	VSP	VSP	VSP	EXP	EXP	VSP
D6	**BIOM**	SLN	VSN	VSP	EQP	EQP	EQP
	CHEM	SLN	VSP	EXP	VSN	SLP	SLP
	ADSP	EQP	SLP	SLP	SLP	SLP	EQP
	BIOD	SLP	EQP	EXN	SLN	SLP	SLP
	PHRM	EQP	VSP	VSP	EXP	VSP	VSP
	CBIR	VSP	EXP	EXP	SLP	VSP	EXP
D7	**BIOM**	SLN	VSN	SLP	EQP	VSP	SLP
	CHEM	SLN	EXP	SLP	EXN	EQP	VSP
	ADSP	VSP	EQP	EQP	SLP	SLP	EQP
	BIOD	EXN	EQP	EXN	EQP	SLP	VSP
	PHRM	EQP	SLP	VSP	EXP	EXP	VSP
	CBIR	SLP	EXP	EXP	EXP	EXP	VSP
D8	**BIOM**	SLN	SLP	SLP	EQP	VSN	EQP
	CHEM	EXP	EQP	EXN	VSN	SLP	VSP
	ADSP	EQP	VSP	EXP	VSN	VSP	SLP
	BIOD	EQP	SLP	SLP	SLP	EXP	SLP
	PHRM	EXP	EQP	EXN	SLN	EQP	VSP
	CBIR	VSP	SLP	EXP	VSP	VSN	EXP
D9	**BIOM**	VSN	EXN	EQP	SLN	SLP	EQP
	CHEM	EQP	SLN	SLN	VSN	SLN	SLP
	ADSP	EQP	SLN	SLP	EQP	VSP	SLN
	BIOD	SLP	SLP	EQP	SLP	EQP	EQP
	PHRM	VSP	VSP	EXP	EXP	EXP	EXP
	CBIR	EXP	VSP	EXP	VSP	VSP	EXP
D10	**BIOM**	SLN	VSP	EXP	SLP	SLP	EQP
	CHEM	EQP	VSP	SLP	SLN	SLP	SLP
	ADSP	EXP	VSP	VSP	SLN	SLP	SLP
	BIOD	SLP	VSN	EQP	EXP	SLP	SLN
	PHRM	SLP	EXP	EXN	SLN	VSP	EXP
	CBIR	SLN	EQP	SLP	EXP	VSP	VSP
D11	**BIOM**	EQP	VSN	SLP	EQP	SLN	EQP
	CHEM	SLN	VSP	VSP	SLN	EQP	EQP
	ADSP	EQP	SLP	EXP	SLP	SLN	VSP

	BIOD	SLP	EQP	EQP	SLP	EXN	EXP
	PHRM	EQP	VSP	VSN	VSP	SLN	VSP
	CBIR	VSP	EXP	EXP	VSP	SLP	SLP
D12	**BIOM**	VSN	SLN	EXP	VSP	VSN	SLP
	CHEM	VSN	VSP	EQP	SLN	SLN	SLP
	ADSP	SLP	EXP	EQP	EXN	SLP	EQP
	BIOD	VSN	EQP	SLP	SLP	EQP	EXP
	PHRM	VSP	EQP	EXN	VSP	EXN	VSP
	CBIR	VSP	EXP	VSP	EXP	VSP	EXP

Appendix 3. Best $\tilde{f}^*$ and the worst $\tilde{f}^-$ for all criteria

Criteria		$\tilde{f}^*$	$\tilde{f}^-$
OECI	**l**	0.6542	0.0842
	m	0.8175	0.2225
	u	0.9442	0.3883
FLEX	**l**	0.7075	0.1817
	m	0.8742	0.3467
	u	0.9583	0.5133
FOAM	**l**	0.7492	0.1658
	m	0.9158	0.2792
	u	0.9858	0.4450
EFFC	**l**	0.7492	0.0425
	m	0.9158	0.1675
	u	0.9858	0.3325
REST	**l**	0.6533	0.3458
	m	0.8183	0.5008
	u	0.9300	0.6533
SECC	**l**	0.7225	0.3733
	m	0.8875	0.5425
	u	0.9858	0.7092

Appendix 4. Fuzzy differences $\tilde{d}_{ij}$

Criteria		BIOM	CHEM	ADSP	BIOD	PHRM	CBIR
OECI	**l**	0.3091	0.0484	-0.0310	-0.0446	-0.0310	-0.3372
	m	0.6919	0.4186	0.3372	0.3343	0.3382	0.0000
	u	1.0000	0.7597	0.6783	0.6618	0.6773	0.3372
FLEX	**l**	0.2500	-0.2876	-0.2328	0.1062	-0.2876	-0.3230
	m	0.6792	0.0912	0.1245	0.5172	0.0719	0.0000
	u	1.0000	0.4099	0.4474	0.8412	0.3938	0.3230
FOAM	**l**	-0.1189	-0.0518	-0.1870	0.3709	0.0152	-0.2886
	m	0.2348	0.3039	0.1514	0.7764	0.3384	0.0000
	u	0.5264	0.5762	0.4411	1.0000	0.5762	0.2886
EFFC	**l**	0.1758	0.4417	-0.0150	0.0592	-0.1776	-0.2509
	m	0.5292	0.7933	0.3233	0.3958	0.1042	0.0000
	u	0.7800	1.0000	0.5583	0.6475	0.3525	0.2509
REST	**l**	-0.2111	-0.2354	-0.3538	0.0000	-0.3566	-0.4736

	m	0.3067	0.3310	0.1641	0.5435	0.0956	0.0000
	u	0.7832	0.8060	0.6405	1.0000	0.5464	0.4736
	l	0.0218	-0.2245	-0.1578	-0.1810	-0.4299	-0.4068
SECC	**m**	0.5633	0.3143	0.3837	0.3156	0.0000	0.0449
	u	1.0000	0.7469	0.8150	0.7483	0.4299	0.4748

Appendix 5. $\tilde{S}_i$, $\tilde{R}_i$ and $\tilde{Q}_i$ values, i = 1, 2, …, 6, for all technical treatments

	$\tilde{S}_1$	$\tilde{S}_2$	$\tilde{S}_3$	$\tilde{S}_4$	$\tilde{S}_5$	$\tilde{S}_6$
l	0.3376	-0.1806	-0.3707	0.1436	-0.4311	**-0.8367**
m	1.8403	1.1760	0.8210	1.6290	0.6297	0.0162
u	**3.6569**	2.9279	2.4825	3.4381	2.1574	1.4845
	$\tilde{R}_1$	$\tilde{R}_2$	$\tilde{R}_3$	$\tilde{R}_4$	$\tilde{R}_5$	$\tilde{R}_6$
l	0.2313	0.0979	-0.0033	0.1391	0.0057	**-0.0556**
m	0.6342	0.3837	0.3091	0.4193	0.3100	0.0162
u	**0.9717**	0.7382	0.6591	0.7592	0.6581	0.3277
	$\tilde{Q}_1$	$\tilde{Q}_2$	$\tilde{Q}_3$	$\tilde{Q}_4$	$\tilde{Q}_5$	$\tilde{Q}_6$
l	-0.1745	-0.2971	-0.3675	-0.2410	-0.3699	-0.4448
m	0.5038	0.3080	0.2321	0.3757	0.2113	0.0000
u	1.0000	0.8052	0.7172	0.8722	0.6806	0.4448

Appendix 6. Crisp values of S_i, R_i and Q_i, i = 1, 2, …, 6, for all technical treatments

	S_1	S_2	S_3	S_4	S_5	S_6
Crisp	1.9449	1.3078	0.9776	1.7369	0.7853	**0.2213**
	R_1	R_2	R_3	R_4	R_5	R_6
Crisp	0.6124	0.4066	0.3216	0.4392	0.3246	**0.0961**
	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6
Crisp	**0.4431**	0.2720	0.1939	0.3356	0.1740	0.0000

References

Abdoulmoumine, N., Adhikari, S., Kulkarni, A., Chattanathan, S., 2015. A review on biomass gasification syngas cleanup. Appl. Energy 155, 294-307.

Alvarez Etxeberria, I., Garayar, A., Calvo Sánchez, J.A., 2015. Development of sustainability reports for farming operations in the Basque Country using the Delphi method. Rev. Contab. 18 (1), 44-54.

Anojkumar, L., Ilangkumaran, M., Vignesh, M., 2015. A decision making methodology for material selection in sugar industry using hybrid MCDM techniques. Int. J. Mater. Prod. Tec. 51 (2), 102-126.

Ayodele, T.R., Ogunjuyigbe, A.S.O., Alao, M.A., 2018. Economic and environmental assessment of electricity generation using biogas from organic fraction of municipal solid waste for the city of Ibadan, Nigeria. J. Clean. Prod. 203, 718-735.

Bailon, L., Hinge, J., 2014. Biogas upgrading. Evaluation of methods for H_2S removal. Danish Technological Institute.

Burke, A., Winnick, J., Xia, C., Liu, M., 2002. Removal of hydrogen sulfide from a fuel gas stream by electrochemical membrane separation. J. Electrochem. Soc. 149 (11), 160-166.

Canto-Perello, J., Martinez-Garcia, M.P., Curiel-Esparza, J., Martin-Utrillas, M., 2015. Implementing sustainability criteria for selecting a roof assembly typology in medium span buildings. Sustainability 7 (6), 6854-6871.

Canto-Perello, J., Martinez-Leon, J., Curiel-Esparza, J., Martin-Utrillas, M., 2017. Consensus in prioritizing river rehabilitation projects through the integration of social, economic and landscape indicators. Ecol. Indic. 72, 659-666.

Canto-Perello, J., Morera-Escrich, J.L., Martin-Utrillas, M., Curiel-Esparza, J., 2018. Restoration prioritization framework for roadway high cut slopes to reverse land degradation and fragmentation. Land Use Policy 71, 470-479.

Cavallini, C., Giorgetti, A., Citti, P., Nicolaie, F., 2013. Integral aided method for material selection based on quality function deployment and comprehensive VIKOR algorithm. Mater. Design. 47, 27-34.

Chacartegui, R., Carvalho, M., Abrahão, R., Becerra, J., 2015. Analysis of a CHP plant in a municipal solid waste landfill in the South of Spain. Appl. Therm. Eng. 91, 706-717.

Cheah, S., Carpenter, D.L., Magrini-Bair, K.A., 2009. Review of mid to high temperature sulfur sorbents for desulfurization of biomass and coal derived syngas. Energy Fuels 23, 5291-5307.

Commission Implementing Decision (EU) 2016/902 of 30 May 2016 establishing best available techniques (BAT) conclusions, under Directive 2010/75/EU of the European Parliament and of the Council, for common waste water and waste gas treatment/management systems in the chemical sector (notified under document C (2016) 3127) (Text with EEA relevance). Official Journal of the European Union L 152/23 of 9 June 2016. http://data.europa.eu/eli/dec_impl/2016/902/oj (last accessed 12.02.18).

Cooke, R.M., Probst, K.N., 2006. Highlights of the expert judgement policy symposium and technical workshop. Resources for the Future, Washington.

Cosic, M., Folic, R., Folic, B., 2016. Multidisciplinary Approach to the Assessment of Seismic Performances and Rehabilitation of Bridges: Nonlinear Analyses, Probability Theory and Optimization Theory. Procedia Eng. 156, 83-90.

Cucchiella, F., D'Adamo, I., Gastaldi, M., 2014. Sustainable management of waste-to-energy facilities. Renew. Sust. Energ. Rev. 33, 719-728.

Curiel-Esparza, J., Cuenca-Ruiz, M.A., Martin-Utrillas, M., Canto-Perello, J., 2014. Selecting sustainable disinfection technique for wastewater reuse projects. Water 6 (9), 2732-2747.

Curiel-Esparza, J., Mazario-Diez, J.L., Canto-Perello, J., Martin-Utrillas, M.G., 2016. Prioritization by consensus of enhancements for sustainable mobility in urban areas. Environ. Sci. Policy 55 (1), 248-257.

Directive (EU) 2015/2193 of the European Parliament and the Council of 25 November 2015 on the limitation of emissions of certain pollutants into the air from medium combustion plants. Official Journal of the European Union. L313. Volume 58. 28 November 2015.

Environment Agency Wales. 2010. Guidance on gas treatment technologies for landfill gas engines. LFTGN06 v2 2010.

Gul, M., Celik, E., Aydin, N., Gumus, A.T., Guneri, A.F., 2016. A state of the art literature review of VIKOR and its fuzzy extensions on applications. Appl. Soft. Comput. 46, 60-89.

Gupta, P., Mehlawat, M.K., Grover, N., 2016. Intuitionistic fuzzy multi-attribute group decision-making with an application to plant location selection based on a new extended VIKOR method. Inf. Sci. 370, 184-203.

Ho, K., Lin, W., Chung, Y., Chen, Y., Tseng, C., 2013. Elimination of high concentration hydrogen sulfide and biogas purification by chemical-biological process. Chemosphere 92 (10), 1396-1401.

Jahan, A., Edwards, K.L., 2013. VIKOR method for material selection problems with interval numbers and target-based criteria. Mater. Design. 47, 759-765.

Köchermann, J., Schneider, J., Matthischke, S., Rönsch, S., 2015. Sorptive H_2S removal by impregnated activated carbons for the production of SNG. Fuel Process. Technol. 138, 37-41.

Liu, T., First, E.L., Hasan, M.M.F., Floudas. C.A., 2016. A multi-scale approach for the discovery of zeolites for hydrogen sulfide removal. Comput. Chem. Eng. 91, 206-218.

Martin-Utrillas, M., Reyes-Medina, M., Curiel-Esparza, J., Canto-Perello, J., 2015. Hybrid method for selection of the optimal process of leachate treatment in waste treatment and valorization plants or landfills. Clean Technol. Envir. 17 (4), 873-885.

Miltner, M., Makaruk, A., Krischan, J., Harasek, M., 2012. Chemical-oxidative scrubbing for the removal of hydrogen sulphide from raw biogas: potentials and economics. Water Sci. Technol. 66, 1354-1360.

Moreno, B., Groppelli, E.S., Campanella, E.A., 2017. Evaluation of biogas upgrading technologies using a response surface methodology for process simulation. J. Clean. Prod. 141, 978-988.

Muñoz, R., Meier, L., Diaz, I., Jeison, D., 2015. A review on the state-of-the-art of physical/chemical and biological technologies for biogas upgrading. Rev. Environ. Sci. Biotechnol. 14 (6), 727-759.

Nam, H., Wang, S., Jeong, H., 2018. TMA and H_2S gas removals using metal loaded on rice husk activated carbon for indoor air purification. Fuel 213, 186-194.

Novakowski, N., Wellar, B., 2008. Using the Delphi Technique in Normative Planning Research: Methodological Design Considerations. Environ. Plann. A, 40 (6), 1485-1500.

Okoli, C., Pawlowski, S. D., 2004. The Delphi method as a research tool: an example, design considerations and applications. Inform. Manage. 42, 15-29.

Opricovic, S., 1998. Multi-Criteria Optimization of Civil Engineering Systems. Faculty of Civil Engineering, Belgrade.

Opricovic, S., 2011. Fuzzy VIKOR with an application to water resources planning. Expert Syst. Appl. 38 (10), 12983-12990.

Opricovic, S., Tzeng, G.H., 2004. Compromise solution by MCDM methods: a comparative analysis of VIKOR and TOPSIS. Eur. J. Oper. Res. 156, 445-455.

Osorio-Tejada, J.L., Llera-Sastresa, E., Scarpellini, S., 2017. A multi-criteria sustainability assessment for biodiesel and liquefied natural gas as alternative fuels in transport systems. J. Nat. Gas. Sci. Eng. 42, 169-186.

Ozekmekci, M., Salkic, G., Fellah, M.F., 2015. Use of zeolites for the removal of H_2S: A mini-review. Fuel Process. Technol. 139, 49-60.

Paris Agreement, Dec. 12, 2015. United Nations. Framework Convention on Climate Change. Conference of the Parties. Twenty-first session, Paris, 30 November to 11 December. 2015FCCC/CP/2015/L.9/Rev.1, http://unfccc.int/files/essential_background/convention/application/pdf/english_paris_agreement.pdf; (last accessed 16.07.17).

Ren, J., Manzardo, A., Mazzi, A., Zuliani, F., Scipioni, A., 2015. Prioritization of bioethanol production pathways in China based on life cycle sustainability assessment and multicriteria decision-making. Int. J. Life Cycle Ass. 20 (6), 842-853.

Ryckebosch, E., Drouillon, M., Vervaeren, H., 2011. Techniques for transformation of biogas to biomethane. Biomass Bioenerg. 35, 1633-1645.

Sayadi, M.K., Heydari, M., Shahanaghi, K., 2009. Extension of VIKOR method for decision making problem with interval numbers. Appl. Math. Model. 33, 2257-2262.

Sebok, E., Refsgaard, J.C., Warmink, J.J., Stisen, S., Jensen, K.H. 2016. Using expert elicitation to quantify catchment water balances and their uncertainties. Water Resour. Res. 52 (7), 5111-5131.

Sierra, L.A., Yepes, V., Pellicer, E., 2018. A review of multi-criteria assessment of the social sustainability of infrastructures. J. Clean. Prod. 187, 496-513.

Tosic, N., Marinkovic, S., Dasic T, Stanic M., 2015. Multicriteria optimization of natural and recycled aggregate concrete for structural use. J. Clean. Prod. 87, 766-776.

Soner, O., Celik, E., Akyuz, E., 2017. Application of AHP and VIKOR methods under interval type 2 fuzzy environment in maritime transportation. Ocean. Eng. 129, 107-116.

Wang, Z., Ren, J., Goodsite, M.E., Xu, G., 2018. Waste-to-energy, municipal solid waste treatment, and best available technology: Comprehensive evaluation by an interval-valued fuzzy multi-criteria decision making method. J. Clean. Prod. 172, 887-899.

Wu, Z., Ahmad, J., Xu, J., 2016a. A group decision making framework based on fuzzy VIKOR approach for machine tool selection with linguistic information. Appl. Soft. Comput. 42, 314-324.

Wu, Y., Chen, K., Zeng, B., Xu, H., Yang, Y., 2016b. Supplier selection in nuclear power industry with extended VIKOR method under linguistic information. Appl. Soft. Comput. 48, 444-457.

Zadeh, L.A., 1965. Fuzzy sets. Inf. Control. 8 (3), 338-353.

Zadeh, L.A., 1975. The concept of a linguistic variable and its application to approximate reasoning. Inf. Sci. 8 (3), 199-249.

Zadeh, L.A., 2015. Fuzzy logic - a personal perspective. Fuzzy Set Syst. 281, 4-20.

Zhang, X., Tu, Z., Li, H., Huang, K., Hu, X., Wu, Y., MacFarlane, D., 2017. Selective separation of H_2S and CO_2 from CH_4 by supported ionic liquid membranes. J. Membrane Sci. 543, 282-287. https://doi.org/10.1016/j.memsci.2017.08.033.

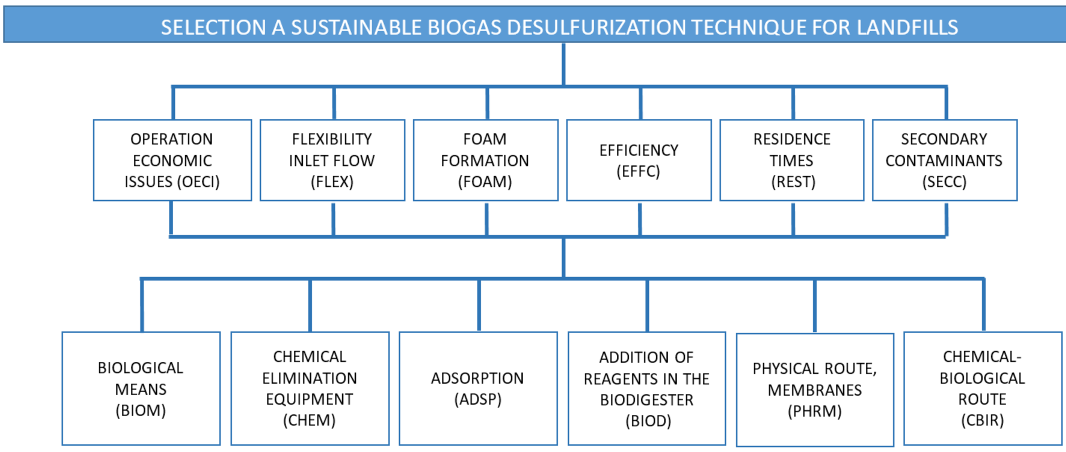

Fig. 1. Hierarchical framework analysis of the criteria and desulfurization techniques.

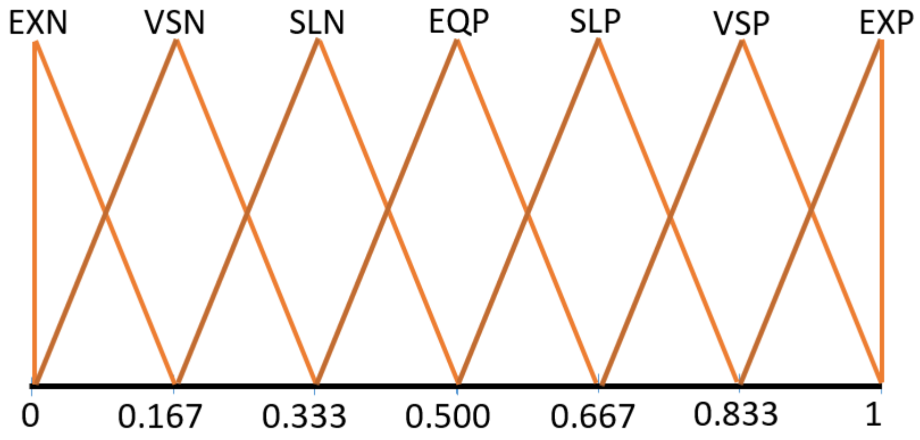

Fig. 2. Triangular membership functions describing linguistic terms.

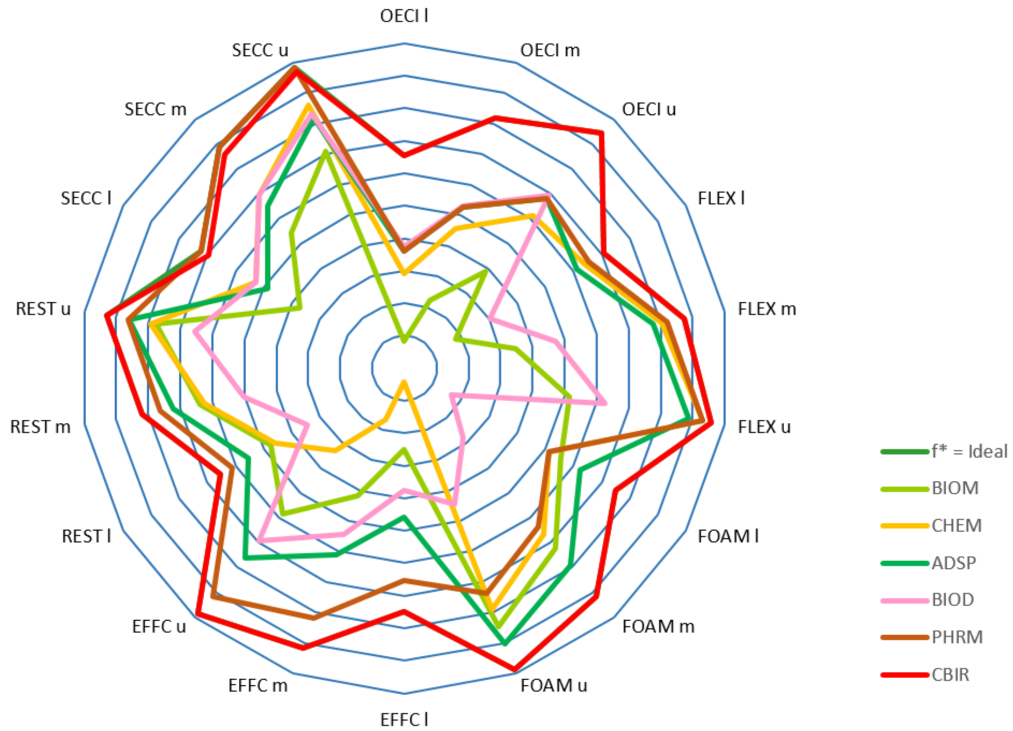

Fig. 3. Differences between each desulfurization technique and the ideal value.