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A MCDA-Based Assessment of Biomethane Generation and Use in Sardinia

Carla ASQUER[1*], Francesco ROMAGNOLI[2]

[1]*Sardegna Ricerche, Renewable Energy Centre, VI Strada Ovest, Z.I. Macchiareddu (Cagliari), 09010, Italy*

[2]*Institute of Energy Systems and Environment, Faculty of Electrical and Environmental Engineering, Riga Technical University, 12/1 Azenes iela, Riga, LV1048, Latvia*

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***Abstract* – The selection of a local and sustainable use of biogas, and biogas feedstocks, towards the upgrading process to biomethane, is a key aspect towards more consistent energy planning within the frame of the EU Green Deal and Sustainable Development Goals. In this paper, four biomethane production and utilization pathways were assessed in the view of economic, environmental, technological, and social dimensions compared to a reference scenario in which direct biogas use in a cogeneration unit is assumed. The technologies analyzed included membrane systems, amine scrubbing, water scrubbing, and biological methanation, regarding the Sardinian context. The impact assessment was carried out using the TOPSIS method. As an output, thirteen consistent indicators reflecting the holistic aspect of sustainability were designed and proposed based on an in-depth literature review and the authors' technological knowledge. The results show that the reference scenario was the preferable one. In terms of environmental and social considerations, biological methanation emerged as the most environmentally and socially responsible alternative. From the economic perspective, all the upgrading options depicted similar results. The technological-oriented weighting showed that the two most widespread upgrading options highlighted the optimal results.**

***Keywords* – Biogas upgrading; biological methanation; biomethane; multi-criteria analysis.**

1. INTRODUCTION

To pursue sustainability, the United Nations established, through the Agenda 2030, 17 Sustainable Development Goals (SDGs) the European Green Deal strategy is coherent to [1], and which represent interconnected targets within the economic, environmental, and social dimensions of development [2].

Energy is a founding element of sustainable development because it supports the activities in every economic sector. In particular, bioenergy is a primary energy source that gives the opportunity of coping with the objectives of fuel switch, resource efficiency, and the deployment of renewables. Among them, biomethane is an advanced biofuel [3] which well integrates with this new energy paradigm.

A panoply of pathways to produce and use biomethane may be found in the literature [4]. Vilardi *et al*. [5] described and compared in detail, mainly in terms of exergy and energy

* Corresponding author.
E-mail address: asquer@sardegnaricerche.it

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assessment, the upgrading techniques of water scrubbing, amine scrubbing, and membrane separation. In the study of Chen X.Y. *et al.* [6], membrane technologies were deeply discussed, and a comparison with other options for biogas upgrading, i.e., organic physical scrubbing, pressure swing adsorption, and water or amine scrubbing, was provided. The upgrading processes of water scrubbing, amine washing, cryogenic separation, and caustic wash were simulated and compared by Hosseinipour and Mehrpooya [7]. A review of biomethane production and utilization options was proposed by Pavičić *et al.* [8], who also considered water scrubbing, amine scrubbing, and membrane and examined physical scrubbing, pressure swing adsorption, vacuum swing adsorption, temperature swing adsorption, and cryogenic separation. A comprehensive review of the upgrading technologies is presented in the report released by the Swedish company Svenskt Gastekniskt CenterAB (SGC) [9]. Another upgrading technology review was presented by the Technische Universität Wien [10].

The literature suggests that the most well-established solutions to produce biomethane from anaerobic digestion biogas are membrane, amine scrubbing, and water scrubbing, which find applications at the commercial scale.

In recent years, *ex-situ* biological methanation has been proposed as a novel technology for biological upgrading. An example was provided by the study of Vo T.T.Q *et al.* [11], who proposed an exhaustive study of biomethane production pathways, including amine scrubber and *ex-situ* biological methanation as independent or combined treatments. This technology belongs to the ones which use and valorize CO_2 and brings additional value to the so-produced biofuels [12]. Nevertheless, the literature about methanation through biological means is still limited.

On the other side, biomethane's uses may differ: it can be used in heat and electricity generation, injected into the gas grid, or employed as a transport fuel [13], manifesting versatility and reliability that meet the energy system needs. Taken as a whole, the pathways for biomethane generation and utilization should be designed to minimize the unfavorable effects on sustainability. These aspects require a detailed impact assessment [14].

The impact assessment is typically carried out from economic and environmental points of view. Paturska *et al.* [15] focused on the economic assessment of the injection of biomethane into the natural gas pipeline and considered a very complete range of technologies, i.e., water scrubbing, amine scrubbing, membrane separation, physical scrubbing, and pressure swing adsorption. Verbeeck *et al.* [16] provided technical parameters for pressurized water scrubbing, pressurized swing adsorption, amine scrubbing, and gas permeation techniques, and emphasized the economic aspects and the fossil fuels replacement potential. Niesner et al. [17] reviewed the state of the art of upgrading technologies used in Europe, which included water scrubbing, chemical scrubbing, physical scrubbing, pressure swing adsorption, and membrane separation, and assessed them with respect to the technological, economic, and environmental impact. Vo T.T.Q *et al*. [11] carried out a techno-economic assessment of three biomethane production pathways in their already mentioned work, composed of energy and economic analyses. However, though rarely faced as a whole, the consistency toward the sustainable development targets is maximized with the multiple criteria of technological, economic, environmental, and social spheres of interest considered altogether in an integrated approach [18], [19].

To the authors' knowledge, an assessment of technological, economic, environmental, and social dimensions of biomethane production and utilization has not been performed, nor is biological methanation usually included among the upgrading technologies. Similarly, an analysis of the options for biomethane generation and use in Sardinia is missing in the literature. These aspects result in a gap of knowledge that the present work proposes to fulfill.

Based on these premises, the present work aims at addressing the following questions:

- What set of indicators might constitute a suitable integrated assessment method for evaluating the impacts of biomethane production and use?
- What are the results of applying the assessment method in the Sardinian context?

The integrated impact assessment was performed through a multi-criteria decision analysis (MCDA), which consists of methods that allow for facing complex problems with many objectives and whose targets are rooted in multiple spheres. For this reason, it suits the multi-dimensions assessment of sustainability [20]. Among the MCDA methods, the TOPSIS assessment was selected and resulted in a set of consistent indicators reflecting the holistic aspect of sustainability. In addition, the information from the local and regional Sardinian contexts was gathered and supported by the knowledge of the local conditions.

2. METHODOLOGY

2.1. The TOPSIS analysis

The MCDA methods are commonly considered ideal for energy issues. They were applied to the assessment of energy storage technologies [21], biomass production chains [22], wood-based options for heat generation [23], location of biogas production plants [24], [25], and others. Among the MCDA methods, the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) can be identified as one of the most widespread and popular techniques which applies to the energy field [26], [27]. For instance, Hajduk and Jelonek [28] performed an extended study of the literature and found that TOPSIS was the most used method in urban energy. Şengül *et al*. [27] adopted Fuzzy-TOPSIS to define a ranking of renewable energy supply systems. In their work on the identification and prioritization of the barriers to bioenergy development, Irfan *et al*. [29] adopted an approach where an adapted TOPSIS method (Grey Technique for Order of Preference by Similarity to Ideal Solution, G-TOPSIS) and Analytical Hierarchy Process (AHP) were integrated.

The TOPSIS method allows for ranking alternative scenarios according to their closeness to the ideal solution and defines the alternative scenarios to be ranked [30], [31]. The ranking is steered by the assessment indicators, selected through literature analysis to effectively describe the scenarios and highlight their differences. Weighting factors associated with the indicators reflect the decision maker's preference.

Indeed, TOPSIS represents the decision-making problem mathematically through a matrix, after distributive normalization, as expressed by Eq. (1) [30]:

$$\overline{x}_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{n} x_{ij}^{2}}}, \tag{1}$$

where x_{ij} is an element of the matrix, $\overline{x_{ij}}$ is an element of the matrix after distributive normalization, $\{i = 1, \ldots, n\}$ represents the scenarios, and $\{j = 1, \ldots, k\}$ represents the indicators. Linear weighting is calculated as expressed by Eq. (2) [30]:

$$v_{ij} = \overline{x}_{ij} \cdot W_j, \tag{2}$$

where $\overline{x_{ij}}$ is an element of the matrix after distributive normalization, W_j is the weighting factor associated with the indicators $\{j = 1, \ldots, k\}$, and v_{ij} is an element of the normalized and weighted matrix.

Geometrically, these elements correspond to a set of points in a Euclidean space that has as many dimensions as the spheres of interest identified. In this geometrical space, TOPSIS calculates the distance S_i^* between each alternative scenario and the ideal solution v_{ij}^* and the distance S_i^- of the given alternative scenario to the negative ideal solution v_{ij}^- by using the Eq. (3) and Eq. (4), respectively [18].

$$S_i^* = \sqrt{\sum_{j=1}^{k} (v_{i,j} - v_j^*)^2}, \quad i = 1, \ldots, n \tag{3}$$

$$S_i^- = \sqrt{\sum_{j=1}^{k} (v_{i,j} - v_j^-)^2}, \quad i = 1, \ldots, n \tag{4}$$

where:

v_{ij} an element of the normalized and weighted matrix;

v_{ij}^* an element of the matrix representing the ideal situation;

v_{ij}^- an element of the matrix representing the negative ideal situation;

S_i^* distance between each alternative scenario and the ideal solution;

S_i^- distance between each alternative scenario and the negative ideal solution.

Thanks to this calculation, the alternative scenarios are prioritized according to their relative closeness to the ideal point and their separation from the negative ideal point, by using Eq. (5), and the scenario with the highest similarity to the ideal solution is identified [18]

$$C_i^* = \frac{s_i^*}{(s_i^* - s_i^-)}, \quad i = 1, \ldots, n \tag{5}$$

where:

s_i^* distance between each alternative scenario and the ideal solution;

s_i^- distance between each alternative scenario and the negative ideal solution;

C_i^* relative closeness to the ideal point.

At last, the robustness of the assessment model is tested through sensitivity analysis [26], [32] conducted by varying the weighting factors which express diverse decision makers' choices.

2.2. Identification of the alternative scenarios and system boundaries

In the TOPSIS method, the alternative scenarios are defined based on the literature review and the authors' knowledge of both the technological aspects of the processes and the local conditions.

It is acknowledged that once produced through anaerobic digestion, the biogas can be directly used to generate heat and power or upgraded to biomethane, which is typically sent to the gas grid or used as a transport fuel.

The regional requirements and restraints were also crucial for the assessment and determined the scenarios' definition. In Sardinia, 30 anaerobic digesters are installed with a total power capacity of 21 MW [33]. At present, cogeneration is the common usage, although the new economic incentives are shifting the interest to biomethane. Since the gas network is not well-developed in Sardinia yet, the use of biomethane as a transport fuel is practicable and currently preferable. Indeed, as [34] emphasized referring to the Swedish case study, this usage may occur even where the gas grid system is limited, thanks to liquefaction.

Therefore, in this paper, the direct generation of heat and power was assumed as a reference and four upgrading techniques with the subsequent use for transportation were proposed as alternatives. The system boundaries were set till selected type of biogas end use (i.e. conversion to energy or as upgraded fuel). The upgrading techniques selected were membranes, amine scrubbing, water scrubbing, and biological methanation. The former three are the most deployed in the commercial plants operating on the Italian mainland. The latter is encompassed in the assessment because of its innovativeness and growing interest.

Given these assumptions, the alternative scenarios designed in this paper are:

a) Direct use of anaerobic digestion biogas in a CHP unit;
b) Upgrading of the anaerobic digestion biogas employing a membrane system, and use of the obtained biomethane as a transport fuel;
c) Upgrading of the anaerobic digestion biogas employing an amine scrubbing system, and use of the obtained biomethane as a transport fuel;
d) Upgrading of the anaerobic digestion biogas employing a water scrubbing system, and use of the obtained biomethane as a transport fuel;
e) Upgrading of the anaerobic digestion biogas employing biological methanation, and use of the obtained biomethane as a transport fuel.

The scenarios are depicted in Fig. 1. Similar scenarios were defined by [16], who compared the direct use of biogas for the cogeneration of heat and power, and the use of biomethane as a transport fuel.

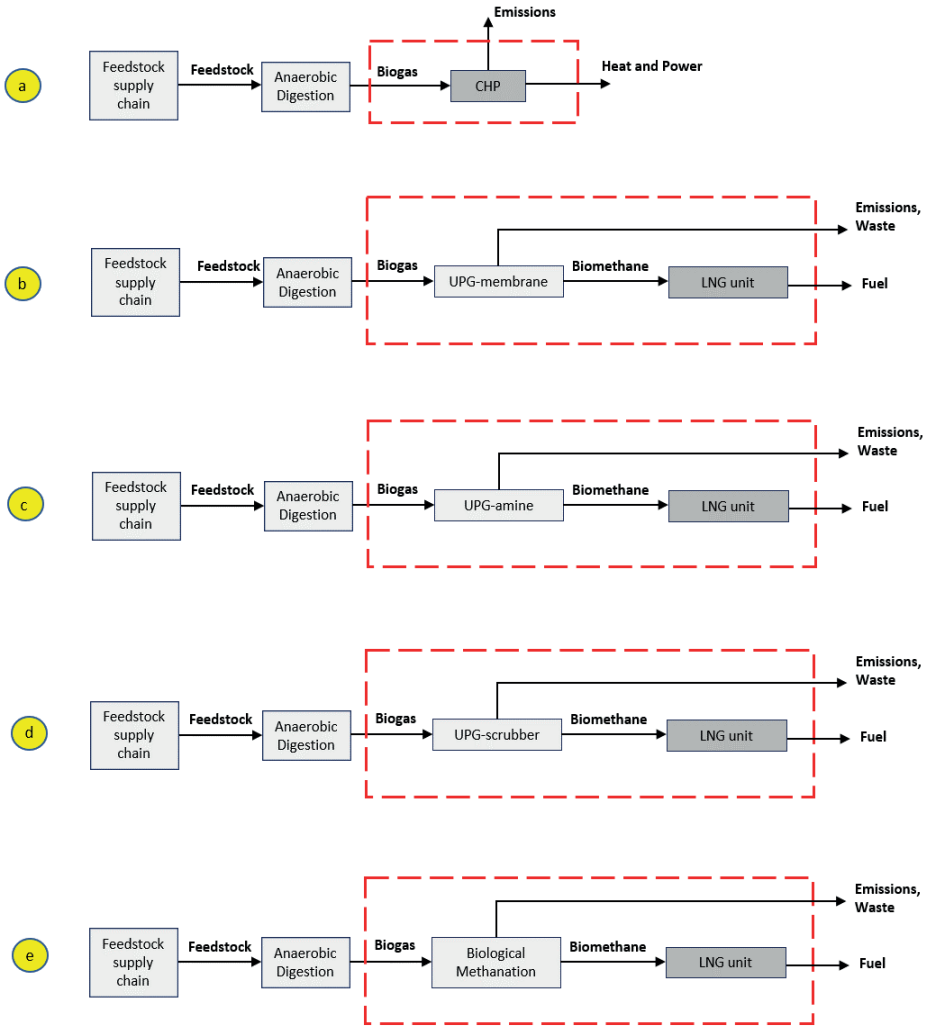

Fig. 1. Selected scenarios for assessing biomethane production and use in Sardinia (CHP: combined heat and power; LNG: liquified natural gas; UPG: upgrading).

2.3. Selection of the indicators in the TOPSIS modelling

The complexity of the areas of interest is a limiting issue for this method, as noted by [18] in reference to the socio-economic perspective, and the selection of the evaluation indicators is of primary concern because they are the means to express it.

The four dimensions of sustainability of biomethane production and utilization (i.e., the economic, environmental, technological, and social spheres of interest) were initially expressed by a set of eighteen indicators selected after literature analysis and in line with the Sustainable Development Goals (SDGs).

The capital investment cost initially described the economic dimension. The other key selected criteria were: the Operational Expenditure (OPEX), the production cost of the energy or fuel produced, and the Energy Return On Investment (EROI) index.

The environmental dimension was addressed by the definition of the Greenhouse Gases (GHG) emission involved in the processes analyzed, primarily carbon dioxide (CO_2) and methane (CH_4). Moreover, the following indicators were also selected as relevant: Disabilitated Adjusted Life per Year (DALY), Potential Disappeared Fraction (PDF), specific energy demand, water footprint, and the volume of final waste.

The conversion efficiency, the possibility of upscaling, and the Technological Readiness Level (TRL) were used to express the technological dimension.

Finally, the social sphere of interest was described by: employment, the local use of final energy, the safety level, the public perception, and the local supply chain development.

This host of indicators was aligned to the criteria expressed in the standard ISO 13065:2015, named Subcriteria for bioenergy, and particularly the reduction of the anthropogenic GHG emissions, the conservation and protection of water resources, the promotion of the efficient use of energy resources, the promotion of positive and the reduction of negative impacts on biodiversity, the promotion of responsible management of waste, the production and trade of bioenergy in an economically and financially viable way, and the respect of labour rights.

However, an in-depth analysis of the processes involved and a thorough and focused literature review showed that thirteen of the initially identified indicators were consistent and they were, therefore, adopted. They represent a key result of the present work and are proposed as a benchmark for future studies. Both qualitative and quantitative indicators were selected, as exposed in the following section.

3. Results and Discussion

3.1. Selected indicators for TOPSIS analysis

The first result of the present work was establishing a set of indicators selected after an exhaustive literature analysis and in-depth knowledge of the evaluated technologies, that the authors proposed as a model for assessing biomethane production and utilization routes. The peculiarity of the proposed indicators is that each has been selected according to two features, i.e., been descriptive of the processes analysed and distinctive of how different the scenarios were. All the selected indicators are reported in Table 1.

The selected economic indicators represent the related sphere of interest in line with the study proposed by Balcioglu *et al.* [35], Bienert *et al*. [41], and Rotunno *et al*. [40]. The capital investment cost (i.e., I1 in Table 1), refers to the initial investment required, while the OPEX (I2) represents the costs required for operating labour, maintenance, and the procurement of consumables and water, and the production cost of the fuel (I3) expresses the price for the unit of biogas or biomethane obtained. The technologies involved in the alternative scenarios respond to these indicators differently, which effectively distinguishes them. The environmental indicators were chosen regarding the characteristics of the proposed processes and are in line with the SDGs [68]. The methane loss (I4) represents a primary greenhouse gases contribution, since its Global Warming Potential is high, i.e. 34 times higher than carbon dioxide, posing the latter equal to 1. Indicators I5 and I6 refer to water usage and the specific energy demand, respectively, and express the specific consumption rates. The chosen indicators emphasize the differences among the alternatives, while other indicators initially considered did not ensure consistency and were not maintained.

TABLE 1. CHARACTERISTICS OF THE ASSESSMENT INDICATORS

Dimension	Indicator	Name	Unit of measure	Type	Min/ Max	References
Economic	I1	Capital investment cost	€·ton$^{-1}_{feedstock}$	Quantitative	Min	[6], [10], [15], [16], [35], [36], [37], [38], [39], [40]
	I2	OPEX	€·ton$^{-1}_{feedstock}$	Quantitative	Min	[6], [10], [16], [35], [36], [37], [39], [40]
	I3	Production cost of the fuel	€·Nm$^{-3}_{biogas}$	Quantitative	Min	[5], [6], [16], [38], [40], [41], [42]
Environmental	I4	Methane loss	%vol.	Quantitative	Min	[5], [6], [7], [16], [17], [35], [37], [41], [42], [43], [44]
	I5	Water demand	L_{water}·m$^{-3}_{biogas}$	Quantitative	Min	[5], [15]
	I6	Specific energy demand	kWh·m$^{-3}_{biogas}$	Quantitative	Min	[1], [5], [6], [7], [15], [34], [39], [40], [42], [45], [46]
Technological	I7	CO_2 separation efficiency	n.a.	Qualitative	Max	[4], [5], [6], [16], [35], [40], [46]
	I8	Need for further polishing steps	n.a.	Qualitative	Min	[5], [6], [7], [9], [16], [35], [36], [40], [41], [42], [46], [47], [48], [49], [50], [51]
	I9	TRL	[unitless]	Quantitative	Max	[1], [5], [6], [8], [36], [41], [42], [50], [52]
	I10	Possibility of upscaling	n.a.	Qualitative	Max	[4], [6], [17], [40], [41], [42], [46], [53], [54], [55], [56]
Social	I11	Safety	n.a.	Qualitative	Max	[5], [7], [40], [49], [57], [58], [59], [60], [61], [62]
	I12	Job creation	Nr. workers	Quantitative	Max	[37], [40], [46], [63], [64], [65], [66], [67]
	I13	Web-based knowledge	n.a.	Qualitative	Max	Google Chrome-Google; Microsoft Edge-Bing; Mozilla Firefox-Google

Referring to the technical indicators, the CO_2 separation efficiency (I7) was selected in substitution for the conversion efficiency because the latter did not distinguish the upgrading processes efficiently. Carbon dioxide impedes its effective use when biomethane is used in the transportation sector. Therefore, CO_2 separation is an important requisite for the scenarios analyzed [5], [6], [43]. Biological methanation does not operate CO_2 separation nor removal, but it converts CO_2 into CH_4. In this way, a carbon dioxide valorization is encountered, providing additional output and increasing the process yields. Thus, this indicator is effective in remarking the differences among the scenarios. Because upgrading processes exhibit different acceptance requirements for the inlet stream in relation to minor compounds, such as O_2 and H_2S, which are typically ignored in impact assessments, the indicator 'need for further polishing steps' (I8) was proposed as relevant. Other requirements are set for allowing biomethane to be accepted in the gas grid and as transport fuel (UNI 16723-1:2016; UNI 16723-2:2017). The biogas direct use in a CHP unit obeys some requirements as well, which are easier to meet than the previously mentioned standards [5], [6], [43]. TRL (I9) is an index of commercial readiness. It is relevant because a well-developed and widespread technology is considered reliable, can be well integrated with existing energy and economic systems, and has robust data on consumptions and yields. Emerging technologies may be unprivileged by this indicator, though. For this reason, the two technologies with the lowest TRL (membrane upgrading and biological methanation) were evaluated given the recent development of the respective demonstrating plants. The first membrane system to purify biogas was built in 1990 [6]. In contrast, only two biological methanation demonstrating plants were built up to

date, in Allendorf-Eder (Germany) in 2014 by MicrobEnergy GmbH (Zürich, Swiss Confederation), and in Avedøre (Denmark) during 2016 by Electrochaea GmbH (Planegg, Germany). While membrane upgrading is more consolidated than biological methanation, the latter is a more promising technology that is expected to spread with commercial-scale plants in the next decades. The possibility of upscaling (I10) is related to the range of plant capacity which can be operated. This indicator is distinctive because the inlet biogas flow rates and the capacity threshold for economic sustainability are diverse for the different technologies [42], [69].

As for the social aspects, [70] reported that the population of nearby plants claimed safety (I11) as an issue. The highest risk in power plants and biogas reservoirs resides in fire and explosion, of which the release of toxic gases is a consequence [71]. Asphyxiation and poisoning are due to carbon dioxide, hydrogen sulfide, and ammonia, which are related to the biogas production process [61], [72]. Other risks are caused by the presence of hazardous compounds such as amines. Concerning the fire and explosion risks, the operating pressure, the addition of hydrogen, and the complexity of installations with the subsequent probability of mechanical breakdowns and leaks [73], [74] differentiate the scenarios. Job creation (I12) is associated with direct employment, stable positions evenly spread over the plant operating life, and R&D and highly skilled jobs arising from highly technological processes [53], [67]. This indicator allows for distinguishing among the scenarios because the different technology level implies variations in the number of operators employed. Smaller installations allow higher local employment, which is particularly important in rural economies. At last, web-based knowledge (I13) compares the consumers' accessibility to information from the web. This indicator is explained by the importance of the public awareness [75] and expresses the differences in the amount of news accessible from the web. The indicator was structured in a way that three combinations of browser and web search engines were used (i.e., Mozilla Firefox and Google, Google Chrome and Google, Microsoft Edge and Bing) to query 54 tags that included the Italian words for: 'Sardinia', 'biogas', 'biomethane', 'upgrading', 'membrane', 'amine', 'scrubber', 'biological methanation', 'biomethanation', and the names of four of the most popular Sardinian television channels. The number of results obtained for each tag, and the combination of browser and web search engine, were compared, and the differences among the technologies involved in the diverse scenarios were found. The importance of this indicator can be explained by the study of [70], who found that people had scarce knowledge of biogas issues and that it generated feelings of uncertainty and doubt about its environmental and economic sustainability.

Both quantitative and qualitative indicators were included in the thirteen above described. The former ones were associated with the input value calculated as the average of the data collected from the literature. The values posed on the latter were included in the range of 1 to 5, representing ratings based on the properties deduced from the literature review.

Another peculiarity of the set of indicators proposed is that some of them are inherent to the upgrading technology, and others are extended to the coupled technology and final utilization. In the first case, the authors imposed a neutral impact on the utilization option so that inequalities in the assessment were not inferred.

3.2. The assessment of biomethane production and utilization pathways in Sardinia

The outcome of the TOPSIS method referring to the indicators reported in Table 1 and tailored to the Sardinian context are presented in this section. For each indicator, specific values were selected. These were obtained from an in-depth literature review and information gathered from expert consultations. Further, a TOPSIS method's distributive normalization

was selected to make a fair comparison among the scenarios. The matrix with the applied normalization is represented in Table 2.

TABLE 2. NORMALIZED MATRIX FOR THE ASSESSMENT INDICATORS AND THE ALTERNATIVE SCENARIOS

			Scenarios				
Dimension	**Indicator**	**Unit of measure**	**a**	**b**	**c**	**d**	**e**
Economic	I1	$€ \cdot ton^{-1}_{feedstock}$	0.021	0.446	0.497	0.492	0.558
	I2	$€ \cdot ton^{-1}_{feedstock}$	0.323	0.426	0.468	0.402	0.578
	I3	$€ \cdot Nm^{-3}_{biogas}$	0.335	0.514	0.402	0.492	0.469
Environmental	I4	%vol.	0.055	0.936	0.219	0.174	0.208
	I5	$L_{water} \cdot m^{-3}_{biogas}$	0.000	0.000	0.135	0.991	0.000
	I6	$kWh \cdot m^{-3}_{biogas}$	0.000	0.475	0.507	0.540	0.475
Technological	I7	n.a.	0.171	0.514	0.686	0.343	0.343
	I8	n.a.	0.641	0.480	0.160	0.320	0.480
	I9	[unitless]	0.518	0.311	0.518	0.518	0.311
	I10	n.a.	0.544	0.272	0.408	0.408	0.544
Social	I11	n.a.	0.686	0.343	0.171	0.343	0.514
	I12	Nr. workers	0.129	0.387	0.516	0.387	0.645
	I13	n.a.	0.762	0.457	0.152	0.305	0.305

Given the previously mentioned data, the results of the TOPSIS assessment are based on the assignment of weighting factors to the indicators in relation to the sphere of interest they belonged to. A sensitivity analysis is conducted by varying the weighting factors, whose ratings are summarized in Annex I.

Rating 1 describes the baseline conditions, where the weighting factors of the economic, environmental, technological, and social spheres of interest were 24 %, 24 %, 28 %, and 24 %, respectively.

Ratings 2 to 5 represent shifted situations, i.e., economic-oriented, environmental-oriented, technological-oriented, and social-oriented. In those alternatives, the economic, environmental, technological, and social dimensions weighted 60 %, 60 %, 64 %, and 60 %, respectively. The indicators within each sphere of interest were equally weighted.

The calculation was performed with the aim of a spreadsheet reported in Annex II.

After calculating Eq. (3) to Eq. (5), the Relative Closeness to the Ideal solution (RCIS) for each scenario was found, represented in Fig. 2.

The results showed that the reference scenario might be the most preferable under the baseline, and the economic-, environmental-, and social-oriented conditions (Ratings 1, 2, 3, and 5, respectively). This could be explained by the fact that the direct cogeneration of heat and power is the most widespread, well-known, affordable, and reliable solution for using biogas and does not require water, energy consumption, hazardous reagents, and other installations with additional costs. This is consistent with what was obtained by [18], who also found that the biogas upgrading with injection into the gas grid and subsequent utilization in a CHP unit was the second most preferred option.

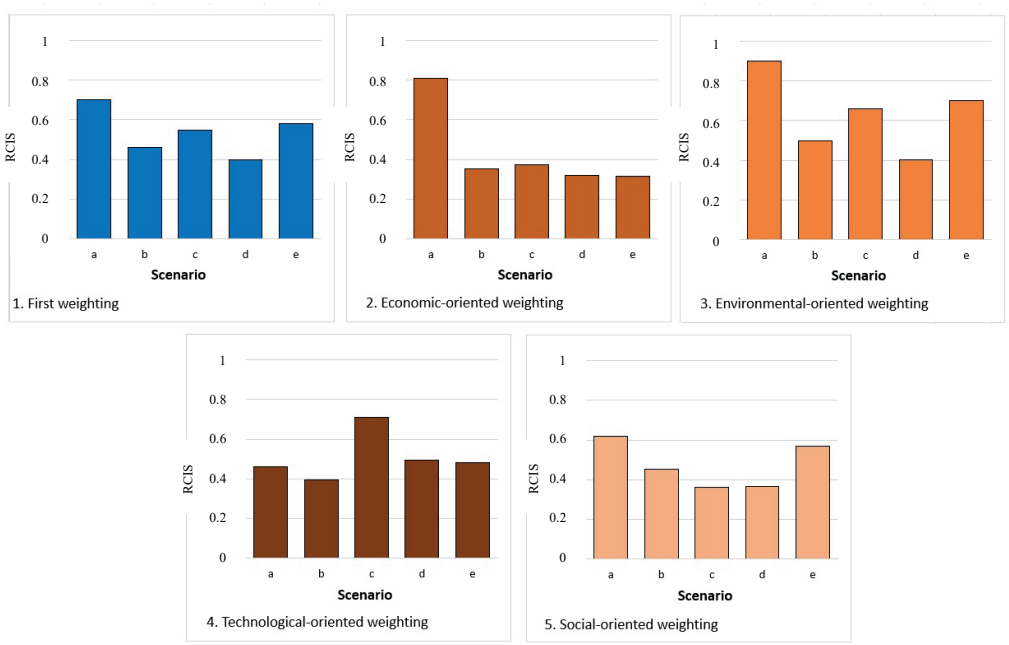

Fig. 2. TOPSIS results for the biomethane production and utilization pathways in the Sardinian context (RCIS: Relative Closeness to the Ideal Solution).

In the present work, biological methanation resulted as the most sustainable option among the alternative biomethane routes, according to the baseline condition (Rating 1) and the environmental- and the social-oriented conditions (Rating 3 and 5, respectively). This can be explained mainly by:

- the advantageous process operating conditions of biological methanation, i.e. lower pressure than the other upgrading techniques, and exothermal reactions at mesophilic or thermophilic regimes, which limit the specific energy demand;
- the short volume of process wastewater;
- the opportunity for highly skilled and local job positions without dependence on external suppliers.

On the other hand, it is necessary to remark on the importance of the hydrogen production pathway, which was not considered in the boundaries of the proposed analysis. The presented results considered the hypothesis that excess renewable energy was used to operate electrolyzers and generate hydrogen so that no energy had to be supplied. Otherwise, it would have negatively influenced the results from environmental and economic perspectives.

All the alternative upgrading options manifested similar values under the economic-oriented condition (Rating 2), which might suggest that all the technologies are equally competitive and promising because a decrease in investment and costs can be predicted. It is noticeable that the most emerging technology, i.e., biological methanation, exhibited similar economic features to the other more consolidated upgrading options, possibly because of the minor plant complexity.

The technological-oriented evaluation favoured the scenario composed of the amines upgrading, followed by water scrubbing, and the use as a transport fuel. The technological

advantages of the two most widespread upgrading options highlighted by the present study appear to confirm the validity of the model proposed.

4. CONCLUSION

In order to fill a knowledge gap in the impact assessment of biomethane production and utilization pathways, four routes were assessed in the view of economic, environmental, technological, and social dimensions. The impact assessment was conducted using the TOPSIS method. This Multi-Criteria Analysis approach involved scenarios where membrane systems, amine scrubbing, water scrubbing, and biological methanation were considered to produce biomethane for the transportation sector. The alternatives referred either to the most common upgrading options or the emerging biomethanation technique. Biomethane utilization for transport was proposed because practicable even though the gas grid is limited, as in the local context under study. The reference scenario consisted of the direct use of biogas for the cogeneration of heat and power.

The objectives of this work were the proposal of a set of indicators which constitute a suitable assessment method for evaluating the impacts of biomethane production and use, and the application of the method to the Sardinian case study.

Based on the indicators, which were selected after an exhaustive literature analysis, experts' opinions, and in-depth knowledge of the technologies, the obtained results for the Sardinian context were the following. The reference scenario was preferred in 80 % of the investigated conditions, each oriented towards one of the mentioned sustainability dimensions, while the biological methanation was the second most sustainable option from the environmental and social point of view. Amine scrubbing, one of the most widespread upgrading solutions, was the preferred option from the technological view and the second one from the economic perspective. These results suggest that the sensitivity analysis supported and validated the proposed model outcomes.

As a conclusion, the present paper provides an assessment model for the use of biogas at a local level and may represent a tool for regional environmental or community planning. However, it can be adapted for applications in other regional contexts, and future improvements would be achieved if robust and reliable quantitative data were available, limiting the employment of qualitative indicators.

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REFERENCES

[1] Pakere I., Prodanuks T., Kamenders A., Veidenbergs I., Holler S., Villere A., Blumberga D. Ranking EU climate and energy policies. *Environmental and Climate Technologies* 2021:25:1:367–381. https://doi.org/10.2478/rtuect-2021-0027

[2] Londoño-Pineda A. A., Cano J. A. Assessments under the United Nations Sustainable Development Goals: A bibliometric analysis. *Environmental and Climate Technologies* 2022:26:1:166–181. https://doi.org/10.2478/rtuect-2022-0014

[3] Directive 2018/2001/EC of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (Renewable Energy Directive II). *Official Journal of European Union* 2018:L 328/82–209.

[4] IEA International Energy Agency. Outlook for biogas and biomethane. Prospects for organic growth [Online]. [Accessed: 21.03.2023]. Available: https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/an-introduction-to-biogas-and-biomethane

[5] Vilardi G., Bassano C., Deiana P., Verdone N. Exergy and energy analysis of three upgrading processes. *Energy Conversion and Management* 2020:224:113323. https://doi.org/10.1016/j.enconman.2020.113323

[6] Chen X. Y., Vinh-Thang H., Ramirez A. A., Rodrigue D., Kaliaguine S. Membrane gas separation technologies for biogas upgrading. *RSC Adv*ances 2015:5:24399. https://doi.org/10.1039/C5RA00666J

[7] Hosseinipour S. A., Mehrpooya M. Comparison of the biogas upgrading methods as a transportation fuel. *Renewable Energy* 2019:130:641–655. https://doi.org/10.1016/j.renene.2018.06.089

[8] Pavičić J., Novak Mavar K., Brkić V., Simon K. Biogas and biomethane production and usage: Technology development, advantages and challenges in Europe. *Energies* 2022:15(8):2940. https://doi.org/10.3390/en15082940

[9] Bauer F., Hulteberg C., Persson T., Tamm D. Biogas upgrading: Review of commercial technologies. Svenskt Gastekniskt CenterAB. SGC Rapport, 2013.

[10] Biogas to biomethane technology review. In: Promotion of bio-methane and its market development through local and regional partnership. Task 3.1.1. TU Wien (Technische Universität Wien). Intelligent Energy European programme project, 2012.

[11] Vo T. T. Q., Wall D. M., Ring D., Rajendran K., Murphy J. D. Techno-economic analysis of biogas upgrading via amine scrubber, carbon capture and ex-situ methanation. *Applied Energy* 2018:212:1191–1202. https://doi.org/10.1016/j.apenergy.2017.12.099

[12] Valdmanis G., Bazbauers G., Bataitis M., Bohvalovs G., Lilo J., Blumberga A., Blumberga D. CO_2-to-fuel: Business and institutional aspects of implementation dynamics. *Environmental and Climate Technologies* 2022:26:1:1182–1195. https://doi.org/10.2478/rtuect-2022-0089

[13] Alvarez-Huamani M., Paredes-Zavala J., Davila-del-Carpio G. Sustainability-based life cycle analysis of biomethane as a transportation fuel compared to Diesel and natural gas in Arequipa. *Preprints* 2021:2021110001. https://doi.org/10.20944/preprints202111.0001.v1

[14] Ishizaka A., Nemery P. Multi-Criteria Decision Analysis. Methods and Software. West Sussex (United Kingdom): Wiley, 2013.

[15] Paturska A., Repele M., Bazbauers G. Economic assessment of biomethane supply system based on natural gas infrastructure. *Energy Procedia* 2015: 72:71-78. doi: 10.1016/j.egypro.2015.06.011

[16] Verbeeck K., Buelens L. C., Galvita V. V., Marin G. B., Van Geem K. M., Rabaey K. Upgrading the value of anaerobic digestion *via* chemical production from grid injected biomethane. *Energy and Environmental Science* 2018:11:1788–1802. https://doi.org/10.1039/C8EE01059E

[17] Niesner J., Jecha D., Stehlik P. Biogas upgrading techniques: State of art review in European region. *Chemical Engineering Transactions* 2013:35:517–522. https://doi.org/10.3303/CET1335086

[18] Dzene I., Romagnoli F., Seile G., Blumberga D. Comparison of different biogas use pathways for Latvia: Biogas use in CHP vs. biogas upgrading. *9th International Conference Environmental Engineering*, Vilnius, 2014. https://doi.org/10.3846/enviro.2014.017

[19] Slišāne D., Gaumigs G., Lauka D., Blumberga D. Assessment of energy sustainability in statistical regions of Latvia using Energy Sustainability Index. *Environmental and Climate Technologies* 2020:24:2:160–169. https://doi.org/10.2478/rtuect-2020-0069

[20] Cinelli M., Coles S. R., Kirwan K. Analysis of the potentials of multi criteria decision analysis methods to conduct sustainability assessment. *Ecological Indicators* 2014:46:138–148. https://doi.org/10.1016/j.ecolind.2014.06.011

[21] Vo T. T. Q., Xia A., Rogan F., Wall D. M., Murphy J. D. Sustainability assessment of large-scale storage technologies for surplus electricity using group multi-criteria decision analysis. *Clean Technology Environmental Policy* 2017: 19:689–703. https://doi.org/10.1007/s10098-016-1250-8

[22] Myllyviita T., Holma A., Antikainen R., Lähtinen K., Leskinen P. Assessing environmental impacts of biomass production chains: Application of life cycle assessment (LCA) and multi-criteria decision analysis (MCDA). *Journal of Cleaner Production* 2012:29–30:238–245. https://doi.org/10.1016/j.jclepro.2012.01.019

[23] Martín-Gamboa M., Dias L. C., Quinteiro P., Freire F., Arroja L., Dias A. C. Multi-criteria and life cycle assessment of wood-based bioenergy alternatives for residential heating: A sustainability analysis. *Energies* 2019:12(22):4391. https://doi.org/10.3390/en12224391

[24] Kheybari S., Rezaie F. M. Selection of biogas, solar, and wind power plants' locations: An MCDA approach. *Journal of Supply Chain Management Science* 2020:1:1–2. http://dx.doi.org/10.18757/jscms.2020.4805

[25] Taraszkiewicz N. Agricultural biogas plant location selection using MCDA methods. *Proceedings* 2019:16:7. https://doi.org/10.3390/proceedings2019016007

[26] Bhowmik C., Kaviani M. A., Ray A., Ocampo L. An integrated entropy: TOPSIS methodology for evaluating green energy sources. In: *Research anthology on clean energy management and solutions*. Hershey (PA): IGI Global, 2021. https://doi.org/10.4018/978-1-7998-9152-9.ch010

[27] Şengül Ü., Eren M., Shiraz S. E., Gezder V., Şengül A. B. Fuzzy TOPSIS method for ranking renewable energy supply systems in Turkey. *Renewable Energy* 2015:75:617–625. https://doi.org/10.1016/j.renene.2014.10.045

[28] Hajduk S., Jelonek D. A decision-making approach based on TOPSIS method for ranking smart cities in the context of urban energy. *Energies* 2021:14(9):2691. https://doi.org/10.3390/en14092691
[29] Irfan M., Elavarasan R. M., Ahmad M., Mohsin M., Dagar V., Hao Y. Prioritizing and overcoming biomass energy barriers: Application of AHP and G-TOPSIS approaches. *Technological Forecasting & Social Change* 2022:177:121524. https://doi.org/10.1016/j.techfore.2022.121524
[30] Chakraborty S. TOPSIS and Modified TOPSIS: A comparative analysis. *Decision Analytics Journal* 2022:2:100021. https://doi.org/10.1016/j.dajour.2021.100021
[31] Karklina K., Slisane D., Romagnoli F., Blumberga D. Social life cycle assessment of biomethane production and distribution in Latvia. *Environmental Technology Proceedings of the International Scientific and Practical Conference*, 2015. https://doi.org/10.17770/etr2015vol2.628
[32] Kuleli Pak B., Albayrak Y. E., Erensal Y. C. Renewable energy perspective for Turkey using sustainability indicators. *International Journal of Computational Intelligence Systems* 2015:8:1:187–197. https://doi.org/10.2991/ijcis.2015.8.1.15
[33] GSE. Atlaimpianti, 2023 [Online]. [Accessed 27.03.2023]. Available: https://www.gse.it/dati-e-scenari/atlaimpianti
[34] Ammenberg J., Gustafsson, M., O'Shea R., Gray, N., Lyng K-A., Eklund M., Murphy J. D. Perspectives on biomethane as a transport fuel within a circular economy, energy, and environmental system. Ammenberg, J; Murphy, J.D. (Ed.) *IEA Bioenergy Task* 37 2021:12.
[35] Balcioglu G., Jeswani H.K., Azapagic A. Evaluating the environmental and economic sustainability of energy from anaerobic digestion of different feedstocks in Turkey. *Sustainable Production and Consumption* 2022:32:924–941. https://doi.org/10.1016/j.spc.2022.06.011
[36] Bellini R., Bassani I., Vizzarro A., Azim A. A., Vasile N. S., Pirri C. F., Verga F., Menin B. Biological aspects, advancaments and techno-economical evaluation of biological methanation for the recycling and valorization of CO_2. *Energies* 2022:15(11):4064. https://doi.org/10.3390/en15114064
[37] Goulding D., Power N. Which is the preferable biogas utilisation technology for anaerobic digestion of agricultural crops in Ireland: Biogas to CHP or biomethane as a transport fuel? *Renewable Energy* 2013:53:121–131. https://doi.org/10.1016/j.renene.2012.11.001
[38] Lawson N., Alvarado-Morales M. Tsapekos P., Angelidaki I. Techno-Economic Assessment of Biological Biogas Upgrading Based on Danish Biogas Plants. *Energies* 2021:14(24):8252. https://doi.org/10.3390/en14248252
[39] Murphy J. D., McKeogh E., Kiely G. Technical/economic/environmental analysis of biogas utilization. *Applied Energy* 2004:77(4):407–427. https://doi.org/10.1016/j.apenergy.2003.07.005
[40] Rotunno P., Lanzini A., Leone P. Energy and economic analysis of a water scrubbing based biogas upgrading process for biomethane injection into the gas grid or use as transportation fuel. *Renewable Energy* 2017:102(PB):417–432. https://doi.org/10.1016/j.renene.2016.10.062
[41] Bienert K., Schumacher B., Rojas Arboleda M., Billig E., Shakya S., Rogstrand G., Zieliński M., Dębowski M. Multi-Indicator assessment of innovative small-scale biomethane technologies in Europe. *Energies* 2019:12(7):1321. https://doi.org/10.3390/en12071321
[42] Miltner M., Makaruk A., Harasek M. Review on available biogas upgrading technologies and innovations towards advanced solutions. *Journal of Cleaner Production* 2017:161:1329–1337. https://doi.org/10.1016/j.jclepro.2017.06.045
[43] Johansson N. Production of liquid biogas, LBG, with cryogenic and conventional upgrading technology: Description of systems and evaluations of energy balances. Master Thesis, 2008, Lunds Universitet.
[44] Tauber J., Parravicini V., Svardal K., Krampe J. Quantifying methane emissions from anaerobic digesters. *Water Science & Technology* 2019:80(9):1654–1661. https://doi.org/10.2166/wst.2019.415
[45] Capra F., Magli F., Gatti M. Biomethane liquefaction: A systematic comparative analysis of refrigeration technologies. *Applied Thermal Engineering* 2019:158:113815. https://doi.org/10.1016/j.applthermaleng.2019.113815
[46] Gantenbein A., Kröcher O., Biollaz S. M. A., Schildhauer T. J. Techno-economic evaluation of biological and fluidised-bed based methanation process chains for grid-ready biomethane production. *Frontiers in Energy Research* 2022:9:775259. https://doi.org/10.3389/fenrg.2021.775259
[47] Dupnock T. L., Deshusses M. A. Biological co-treatment of H_2S and reduction of CO_2 to methane in an anoxic biological trickling filter upgrading biogas. *Chemosphere* 2020:256:127078. https://doi.org/10.1016/j.chemosphere.2020.127078
[48] Kougias P. G., Treu L., Peñailillo Benavente D., Boe K., Campanaro S., Angelidaki I. *Ex-situ* biogas upgrading and enhancement in different reactor systems. *Bioresource Technology* 2017:225:429–437. https://doi.org/10.1016/j.biortech.2016.11.124
[49] Ma Y., Guo H., Selyanchyn R., Wang B., Deng L., Dai Z., Jiang X. Hydrogen sulfide removal from natural gas using membrane technology: A review. *Journal of Material Chemistry A* 2021:9:20211–20240. https://doi.org/10.1039/D1TA04693D
[50] Rusmanis D., O'Shea R., Wall D. M., Murphy J. D. Biological hydrogen methanation systems: An overview of design and efficiency. *Bioengineered* 2019:10(1):604–634. https://doi.org/10.1080/21655979.2019.1684607
[51] Voelklein M. A., Rusmanis D., Murphy J. D. Biological methanation: Strategies for *in-situ* and *ex-situ* upgrading in anaerobic digestion. *Applied Energy* 2019:235:1061–1071. https://doi.org/10.1016/j.apenergy.2018.11.006

[52] Antukh T., Lee I., Joo S. and Kim H. Hydrogenotrophs-based biological biogas upgrading technologies. *Frontiers in Bioengineering and Biotechnology* 2022:10:833482. https://doi.org/10.3389/fbioe.2022.833482
[53] CIB Consorzio Italiano Biogas. Biogas 2020. Position paper [Online]. [Accessed 16.02.2023]. Available: https://www.consorziobiogas.it/pubblicazioni-2/
[54] Cucchiella F., D'Adamo I., Gastaldi M., Miliacca M. A profitability analysis of small-scale plants for biomethane injection into the gas grid. *Journal of Cleaner Production* 2018:184:179–187. https://doi.org/10.1016/j.jclepro.2018.02.243
[55] Moschini M. Upgrading to biomethane and power production in SOFC-based cogeneration system: An exergo-economic comparison of biogas conversion alternatives. Tesi di Laurea Magistrale in Ingegneria Energetica e Nucleare, Politecnico di Torino, 2017.
[56] Valli C., Cavaliere A., Ferravante L., Scagliotti M. Un approfondimento sulla metanazione biologica per l'upgrading del biogas a biometano: Fattibilità tecnico-economica e possibile ruolo nella gestione delle rinnovabili non programmabili. (An insight into biological methanation for the upgrading of biogas to biomethane: Technical-economic feasibility and possible role in the management of non-programmable renewables). Ricerca sul Sistema Energetico RSE S.p.A. [Online]. [Accessed: 15.04.2023]. Available: https://www.rse-web.it/rapporti/18007798/ (In Italian).
[57] Ardolino F., Cardamone G. F., Parillo F., Arena U. Biogas-to-biomethane upgrading: A comparative review and assessment in a life cycle perspective. *Renewable and Sustainable Energy Reviews* 2021:139:110588. https://doi.org/10.1016/j.rser.2020.110588
[58] Badr S., Frutiger J., Hungerbuehler K., Papadokonstantakis S. A framework for the environmental, health and safety hazard assessment for amine-based post combustion CO_2 capture. *International Journal of Greenhouse Gas Control* 2017:56:202–220. https://doi.org/10.1016/j.ijggc.2016.11.013
[59] Jia J., Chen Y., Che G., Zhu J., Wang F., Jia P. Experimental study on the explosion characteristics of hydrogen-methane premixed gas in complex pipe networks. *Scientific Reports* 2021:11:21204. https://doi.org/10.1038/s41598-021-00722-8
[60] Kotek L., Trávníček P., Blecha P. Accident analysis of European biogas stations. *Chemical Engineering Transactions* 2015:43:1933-1938. https://doi.org/10.3303/CET1543323
[61] Scarponi G. E., Guglielmi D., Casson Moreno V., Cozzani V. Risk assessment of a biogas production and upgrading plant. *Chemical Engineering Transactions* 2015:43:1921–1926. https://doi.org/10.3303/CET1543321
[62] Seay J., Lunghi E., Rehman A., Fabiano B. Analysis of accident data for the bioenergy sector based on second generation feedstock. *Chemical Engineering Transaction* 2017:57:871–876. https://doi.org/10.3303/CET1757131
[63] EBA European Biogas Association. Companies Catalogue: Members of the European Biogas association [Online]. [Accessed 16.02.2023]. Available: https://www.europeanbiogas.eu/wp-content/uploads/2019/05/Companies-Catalogue-EBA-2018.pdf
[64] Electrochaea GmbH. Electroarchaea Fact Sheet 2019:10 [Online]. [Accessed 16.02.2023]. Available: http://www.electrochaea.com/wp-content/uploads/2019/10/20191030_Press-Kit_Electrochaea.pdf
[65] Hashemi S. E., Kim D., Austbø B. Objective function evaluation for optimization of an amine-based biogas upgrading and liquefaction process. *Industrial and Engineering Chemical Research* 2022:61(19):6562–6574. https://doi.org/10.1021/acs.iecr.1c04378
[66] Kulla M., Novotný L., Pregi L. The role and perception of biogas in the energy transformation in Slovakia. *Geographia Cassoviensis* 2022:16(1). https://doi.org/10.33542/GC2022-1-04
[67] Navigant Netherlands B. V. Gas for climate: Job creation by scaling up renewable gas in Europe. Prepared for: Gas for climate: A path to 2050. Reference No. 203997 [Online]. [Accessed 15th April 2023]. Available: https://gasforclimate2050.eu/wp-content/uploads/2020/03/Navigant-Gas-for-Climate-Job-creation-by-scaling-up-renewable-gas-in-Europe.pdf
[68] Sala S. Triple bottom line, sustainability and sustainability assessment, an overview. In: Biofuels for a more sustainable future. Life Cycle Assessment and Multi-Criteria Decision Making. Amsterdam (The Netherlands): Elsevier Inc., 2020. https://doi.org/10.1016/B978-0-12-815581-3.00003-8
[69] Cucchiella F., D'Adamo I., Gastaldi M. Biomethane: A renewable resource as vehicle fuel. *Resources* 2017:6(4):58. https://doi.org/10.3390/resources6040058
[70] Herbes C., Chouvellon S., Lacombe J. Towards marketing biomethane in France: French consumers' perception of biomethane. *Energy, Sustainability and Society* 2018:8:37. https://doi.org/10.1186/s13705-018-0179-7
[71] Soltanzadeh A., Mahdinia M., Golmohammadpour H., Pourbabaki R., Mohammad-Ghasemi M., Sadeghi-Yarandi M. Evaluating the potential severity of biogas toxic release, fire and explosion: Consequence modeling of biogas dispersion in a large urban treatment plant. *International Journal of Occupational Safety and Ergonomics* 2022. https://doi.org/10.1080/10803548.2022.2041846
[72] Schroeder V., Schalau B., Molnarne M. Explosion protection in biogas and hybrid power plants. *Procedia Engineering* 2014:84:259–272. https://doi.org/10.1016/j.proeng.2014.10.433
[73] Lauri R. Biomethane production: Pressure influence on classification of Atex zones. *Chemical Engineering Transactions* 2022:91. https://doi.org/10.3303/CET2291013

[74] Severi C. A., Pérez V., Pascual C., Muñoz R., Lebrero R. Identification of critical operational hazards in a biogas upgrading pilot plant through a multi-criteria decision-making and FTOPSIS-HAZOP approach. *Chemosphere* 2022:307:135845. https://doi.org/10.1016/j.chemosphere.2022.135845

[75] Priedniece V., Kirsanovs V., Prodanuks T., Veidenbergs I., Blumberga D. Treatment of particulate matter pollution: People's attitude and readiness to act. *Environmental and Climate Technologies* 2020:24(2):231–246. https://doi.org/10.2478/rtuect-2020-0069

ANNEX

TABLE AI. WEIGHTING FACTORS FOR THE ASSESSMENT INDICATORS

	Dimension	Economic	Environmental	Technological	Social
Rating 1	Weight	24 %	24 %	28 %	24 %
	Indicator	I1, I2, I3	I4, I5, I6	I7, I8, I9, 10	I11, I12, I13
	Specific weight	0.08	0.08	0.07	0.08
Rating 2	Weight	60 %	12 %	16 %	12 %
	Indicator	I1, I2, I3	I4, I5, I6	I7, I8, I9, 10	I11, I12, I13
	Specific weight	0.20	0.04	0.04	0.04
Rating 3	Weight	12 %	60 %	16 %	12 %
	Indicator	I1, I2, I3	I4, I5, I6	I7, I8, I9, 10	I11, I12, I13
	Specific weight	0.04	0.20	0.04	0.04
Rating 4	Weight	12 %	12 %	64 %	12 %
	Indicator	I1, I2, I3	I4, I5, I6	I7, I8, I9, 10	I11, I12, I13
	Specific weight	0.04	0.04	0.16	0.04
Rating 5	Weight	12 %	12 %	16 %	60 %
	Indicator	I1, I2, I3	I4, I5, I6	I7, I8, I9, 10	I11, I12, I13
	Specific weight	0.04	0.04	0.04	0.20

TABLE AII. SENSITIVITY ANALYSIS AND RELATED INDICATOR MATRIX FOR SCENARIO.

Rating 1: Baseline													
	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13
a	0.002	0.026	0.027	0.004	0.000	0.000	0.011	0.039	0.036	0.038	0.055	0.010	0.061
b	0.036	0.034	0.041	0.075	0.000	0.038	0.034	0.039	0.022	0.019	0.027	0.031	0.037
c	0.040	0.037	0.032	0.018	0.011	0.041	0.045	0.010	0.036	0.029	0.014	0.041	0.012
d	0.039	0.032	0.039	0.014	0.079	0.043	0.034	0.029	0.036	0.029	0.027	0.031	0.024
e	0.045	0.046	0.038	0.017	0.000	0.038	0.022	0.029	0.022	0.038	0.041	0.052	0.024

Rating 2: Economic-oriented conditions													
	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13
a	0.004	0.065	0.067	0.002	0.000	0.000	0.006	0.022	0.021	0.022	0.027	0.005	0.030
b	0.089	0.085	0.103	0.037	0.000	0.019	0.019	0.022	0.012	0.011	0.014	0.015	0.018
c	0.099	0.094	0.080	0.009	0.005	0.020	0.026	0.006	0.021	0.016	0.007	0.021	0.006
d	0.098	0.080	0.098	0.007	0.040	0.022	0.019	0.017	0.021	0.016	0.014	0.015	0.012
e	0.112	0.116	0.094	0.008	0.000	0.019	0.013	0.017	0.012	0.022	0.021	0.026	0.012

Rating 3: Environmental-oriented conditions													
	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13
a	0.001	0.013	0.013	0.011	0.000	0.000	0.006	0.022	0.021	0.022	0.027	0.005	0.030
b	0.018	0.017	0.021	0.187	0.000	0.095	0.019	0.022	0.012	0.011	0.014	0.015	0.018
c	0.020	0.019	0.016	0.044	0.027	0.101	0.026	0.006	0.021	0.016	0.007	0.021	0.006
d	0.020	0.016	0.020	0.035	0.198	0.108	0.019	0.017	0.021	0.016	0.014	0.015	0.012
e	0.022	0.023	0.019	0.042	0.000	0.095	0.013	0.017	0.012	0.022	0.021	0.026	0.012

Rating 4: Technological-oriented conditions													
	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13
a	0.001	0.013	0.013	0.002	0.000	0.000	0.026	0.090	0.083	0.087	0.027	0.005	0.030
b	0.018	0.017	0.021	0.037	0.000	0.019	0.077	0.090	0.050	0.044	0.014	0.015	0.018
c	0.020	0.019	0.016	0.009	0.005	0.020	0.102	0.022	0.083	0.065	0.007	0.021	0.006
d	0.020	0.016	0.020	0.007	0.040	0.022	0.077	0.067	0.083	0.065	0.014	0.015	0.012
e	0.022	0.023	0.019	0.008	0.000	0.019	0.051	0.067	0.050	0.087	0.021	0.026	0.012

Rating 5: Social-oriented conditions													
	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13
a	0.001	0.013	0.013	0.002	0.000	0.000	0.006	0.022	0.021	0.022	0.137	0.026	0.152
b	0.018	0.017	0.021	0.037	0.000	0.019	0.019	0.022	0.012	0.011	0.069	0.077	0.091
c	0.020	0.019	0.016	0.009	0.005	0.020	0.026	0.006	0.021	0.016	0.034	0.103	0.030
d	0.020	0.016	0.020	0.007	0.040	0.022	0.019	0.017	0.021	0.016	0.069	0.077	0.061
e	0.022	0.023	0.019	0.008	0.000	0.019	0.013	0.017	0.012	0.022	0.103	0.129	0.061