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Decision Support System to Implement Units of Alternative Biowaste Treatment for Producing Bioenergy and Boosting Local Bioeconomy

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Received: 11 April 2020; Accepted: 30 April 2020; Published: 6 May 2020

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Abstract: Lately, the model of circular economy has gained worldwide interest. Within its concept, waste is viewed as a beneficial resource that needs to be re-introduced in the supply chains, which also requires the use of raw materials, energy, and water to be minimized. Undeniably, a strong link exists between the bioeconomy, circular economy, bioproducts, and bioenergy. In this light, in order to promote a circular economy, a range of alternative options and technologies for biowaste exploitation are currently available. In this paper, we propose a generic methodological scheme for the development of small, medium, or large-scale units of alternative biowaste treatment, with an emphasis on the production of bioenergy and other bioproducts. With the use of multi-criteria decision analysis, the model simultaneously considers environmental, economic, and social criteria to support robust decision-making. In order to validate the methodology, the latter was demonstrated in a real-world case study for the development of a facility in the region of Serres, Greece. Based on the proposed methodological scheme, the optimal location of the facility was selected, based on its excellent assessment in criteria related to environmental performance, financial considerations, and local acceptance. Moreover, anaerobic digestion of agricultural residues, together with farming and livestock wastes, was recommended in order to produce bioenergy and bioproducts.

Keywords: bioenergy; efficiency of bio-resources; decision support system; multi-criteria analysis; sustainability

1. Introduction

Circular economy and resource efficiency have received increasing attention in research and environmental policy agenda in recent years. Circularity can be a catalyst for productive reconstruction and has a clear regional dimension, where the value of waste is a key element. Within the concept of circular economy, waste, energy, and water consumption need to be minimized [1–4] and, in any case, the corresponding environmental pressures should respect target or limit values [5]. Bioeconomy focuses on the use of biomass/biowaste in primary production procedures (e.g., agriculture, forestry, fisheries) and substantial valorization of raw materials. Biomass is expected to substantially support the achievement of the EU renewable energy targets [6].

Undoubtedly, there is a strong linkage between the bioeconomy, circular economy, bioproducts, and bioenergy. Streams of excess or end-of-life materials, previously regarded as waste, that originate from anthropogenic activities can be channeled through available technologies (e.g., anaerobic digestion, gasification, pyrolysis) and transmute into useable energy carriers, organic biofertilizer abundant in nutrients, and, in general, original and innovative materials. A characteristic example is the production of biofuel (biogas or syngas), which can be characterized as a major means of energy recovery from biowaste streams. An appreciable amplitude of different technological solutions is currently available for small, medium, or large-scale units of alternative biowaste treatment (UABT), with an emphasis on the production of bioenergy and other bioproducts. Such solutions are based on applications that extend from tailor-made systems, which incorporate existing available facilities (e.g., pumps and storages in an existing farm, buildings for the combined heat and power (CHP) installation etc.), to specialized concepts that are diverse, where the main parts have been pre-manufactured.

Although there are many solutions, biowaste disposal in landfills, or, in the worst case, in uncontrolled open dumps, is still an existing practice internationally [7]. This cannot be considered as a proper managerial approach for biowaste, having in mind the intense environmental load imposed. Apart from aesthetic degradation, impacts comprise air pollution and Green House Gas (GHG) emissions, soil and water contamination, reduced land values, and landscape blight. Consequently, optimal biowaste management constitutes a critical activity that reinforces environmental sustainability by minimizing impacts, especially related to uncontrolled discarding [8–12].

The appropriateness and benefits of each technological solution should be examined carefully to support treatment decisions, considering the type of biowaste, local characteristics, and conditions [13–15]. In the material to follow, a generic methodological scheme was developed and demonstrated to support optimal decision-making in promoting and implementing UABTs. The basic structure and components combine environmental, economic, and social parameters and multi-criteria decision analysis (MCDA) for the optimal site selection of a UABT. Since the early 1980s, Ross and Soland [16] reported that problems involving the location and promotion of such units include multi-criteria considerations and ought to be modelled likewise. Nevertheless, the literature has scarcely studied special waste streams, such as biowaste, centralizing mostly on municipal solid waste (MSW) management [17–22]. MCDA has gained wide acceptance in recent years over quantitative modeling, as MCDA embodies both quantitative as well as qualitative variables [23] and can be tractably combined with other tools, such as life cycle assessment, ecological footprint, and environmental indicators [24]. The approach includes the social criterion (e.g., NIMBY - Not In My Back Yard syndrome), which is usually disregarded [25,26]. It also assists relevant stakeholders, public authorities, and producers by providing a roadmap to the feasibility and essential steps for the development of a micro-to-medium-scale localized UABT. Localization is a prerequisite to achieve economies of scale and an emphasis is given to an optimal location, and the production of bioenergy and other bioproducts [27,28].

In this context, the present work frames a consistent generic methodology and seeks optimal UABT solutions, based on multiple criteria and parameters. More specifically, apart from defining the optimal site for the installation of a new UABT, the proposed methodology also assesses the recommended technological solution, based on the characteristics and quantities of locally available biowaste, as well as its size and capacity. The methodology is demonstrated for a real-world case in the region of Serres, Greece.

2. Methodology: Basic Structure and Components

2.1. Selection of Area and Inventory Analysis

Figure 1 presents the main components and the basic steps of the methodological scheme. More specifically, the first step is to determine the wider area for the development of a UABT (Step 1). Crucial aspects for this decision are the availability, quantity, and quality of biowaste regionally.

Characteristic typologies can be found in the Waste Framework Directive [29] and related regulations, e.g., park and yard waste, animal waste (feces, urine, and manure), kitchen and food waste, vegetal waste (food preparation and products), household and similar wastes, common sludges, mixed waste, undifferentiated materials, etc. To assure smooth replenishment and long-term sustainability of a UABT, it is important to pre-assess the continuing availability and seasonality of biowaste locally. Regional logistics infrastructure, mainly transportation and storage facilities, also need to be considered for the available feedstock, due to their criticality in the unit's viability, since the transportation cost is a crucial parameter for the viability of the logistics network [30]. All the above data can be the output of a strengths, weaknesses, opportunities, and threats analysis, for the area under consideration. This initial stage of the methodology puts forward a pool of available types of biomass as potential feedstock for an UABT.

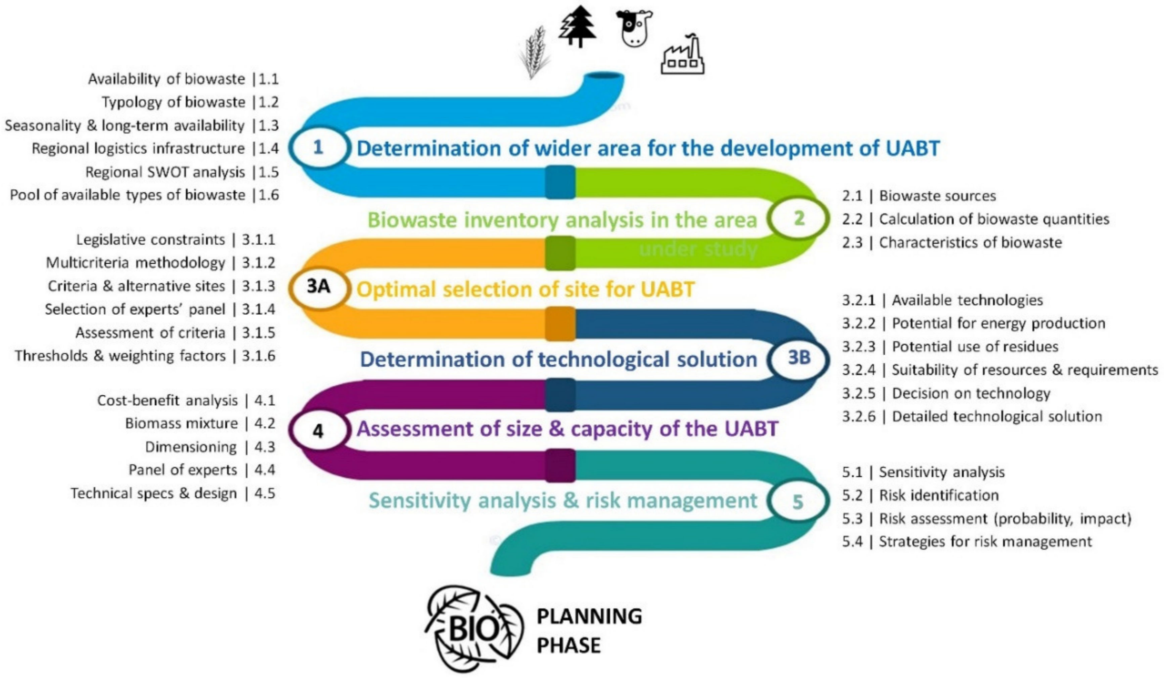


Figure 1. Basic structure and components of the methodological framework.

In the case that an area is considered "eligible" for the development of a UABT, the second step is the preparation of a detailed biowaste inventory analysis that (i) identifies meticulously the biowaste sources, (ii) calculates the available biowaste quantities, and (iii) describes the characteristics of the available biowaste (Step 2). Such an inventory will detail the availability of exploitable biowaste within the region under study and will assist decision-making.

2.2. Optimal Selection of the Site

The inventory analysis is followed by the multiple criteria decision analysis (MCDA) for the optimal location of the UABT (Step 3a). This process is strongly interrelated and usually realized in parallel to the selection of the most appropriate technology (Step 3b). Multi-criteria mathematical modeling examines criteria that are usually in conflict in the decision-making process [31–36]. On this basis, and after screening all legislative constraints (e.g., environmental permits), the appropriate multi-criteria analysis technique needs to be determined. The literature reports a considerable number of techniques available, with different characteristics and uses [37,38]. Multi-criteria analysis techniques are more or less suitable depending on the special characteristics of the case under consideration [39]. In the scientific literature, modelling of waste management solutions mostly takes into account the economic and environmental dimensions of the problem, whilst the social concerns are usually neglected.

Morrissey and Browne [26] meticulously reported sustainable waste management applications. It should be noted that the social pillar constitutes a crucial matter for the future viability of the investment in cases like the one examined in the material to follow. On this basis, social concerns should be simultaneously considered for deciding on the optimal UABT site.

The methodology developed herein adopts the ELECTRE III technique [40]. A main characteristic of this technique is the use of the pseudo-criteria concept in order to depict the different angles of the studied case/problem. ELECTRE III utilizes three pseudo-criteria and initiates a robust comparison of each option with another in relation to all criteria included in the analysis. An ascending and descending distillation process forms the basis for the construction of two complete pre-orders. The intersection of the two complete pre-orders produces a final classification of the alternatives. An advantage of this technique is the sensitive analysis capability. In the framework of the sensitivity analysis, scenarios for the values of the main parameters are performed in order to further test the solution by observing the effect of the adopted values' variation to the result. Comparative assessment of the pre-orders for each scenario leads to a final robust outcome or to a model re-analysis [41]. This technique is widely used in the examination of environmental problems and waste management issues, which provides an advantage to the others [20,33,42–44].

The designation of three thresholds is a prerequisite, i.e., (i) preference threshold (p), (ii) indifference threshold (q), and (iii) veto threshold (v). ELECTRE III uses these thresholds in its mathematical rationale in order to better include real-life uncertainties [41]. Another advantage of this multi-criteria technique is the simultaneous consideration of quantitative (e.g., price of sites, distances, etc.) and qualitative criteria (e.g., landscape degradation, aesthetics, social acceptance, etc.), as this approach depicts a good fit of the data in such applications.

It goes without saying that a meticulous investigation in the wider area under study is needed in order to landmark all the available locations appropriate for the installation of a UABT. As a next step, the assessment of different, usually conflicting, criteria is performed in parallel with defining the weighting factor of each criterion. The weighting factor expresses its relative significance in comparison to the others. A clear definition of the parameters included in the analysis is necessary in order to reliably value all available alternatives and perform the pairwise comparison process. After defining the criteria and weighting factors, the related information and data should be assembled. Multi-criteria evaluation of sites for the UABT location is mathematically formulated with the use of a set of criteria (Cr_1, Cr_2, $Cr_3 \ldots$) applicable to a set of alternatives (A_1, A_2, $A_3 \ldots$). $V_j(A)$ mathematically expresses the evaluation of alternative A i, for the criterion j. ELECTRE III is a ranking method, thus it puts forward a ranking prioritization, which is grounded on binary outranking relations for two interrelated concepts, i.e., (i) concordance (c_j) and (ii) non-discordance (d_j). More specifically, the concept of the concordance relation is applicable when alternative A_1 outranks alternative A_2 in case a sufficient majority of criteria are in favor of alternative A_1. The non-discordance relation is applicable when the concordance condition holds, and none of the criteria in the minority should be opposed strongly to the outranking of A_2 by A_1. The credibility index characterizes the assertion that A_1 outranks A_2 and illustrates the true degree of this assertion [45]. A pair of alternatives is compared for each criterion with the use of pseudo-criteria, namely the indifference (q_j) and preference (p_j) for which they apply:

- When $V_j(A_1) - V_j(A_2) \leq q_j$, then no difference between A_1 and A_2 is identified for the specific criterion j, thus $c_j(A_1, A_2) = 0$.
- When $V_j(A_1) - V_j(A_2) > p_j$, then A_1 is strictly preferred to A_2 for criterion j, thus $c_j(A_1, A_2) = 1$.

The concordance index $c_j(A_1, A_2)$ of each criterion j is mathematically formulated as follows:

$$\begin{array}{l} V_j(A_1) - V_j(A_2) \leq q_j \Leftrightarrow c_j(A_1, A_2) = 0 \\ q_j < V_j(A_1) - V_j(A_2) < p_j \Leftrightarrow c_j(A_1, A_2) = \frac{V_j(A_1) - V_j(A_2) - q_j}{p_j - q_j} \\ V(A_1) - V(A_2) \geq p_j \Leftrightarrow c_j(A_1, A_2) = 1 \end{array} .$$

A global concordance index $C_{A_1A_2}$ for each pair (A_1, A_2) is calculated with the use of c_j (A_1, A_2) as mathematically illustrated below:

$$C_{A_1A_2} = \frac{\sum_{j=1}^{n} w_j \cdot c_j(A_1, A_2)}{\sum_{j=1}^{n} w_j}, w_j \text{ expresses the weighting factor of criterion j.}$$

The discordance index (d_j) is computed with the adoption of indifference (q_j), preference (p_j), and the veto threshold (v_j), which expresses the maximum acceptable difference for not rejecting the assertion A_1 outranks A_2. More specifically:

- When V_j (A_1) − V_j (A_2) ≤ p_j, no discordance exists and therefore d_j (A_1, A_2) = 0.
- When V_j (A_1) − V_j (A_2) > v_j, then d_j (A_1, A_2) = 1.

Thus, d_j (A_1,A_2) is mathematically formulated as:

$$\begin{cases} V_j(A_2) - V_j(A_1) \le p_j \Leftrightarrow d_j(A_1, A_2) = 0 \\ p_j < V_j(A_2) - V_j(A_1) < v_j \Leftrightarrow d_j(A_1, A_2) = \frac{V_j(A_2) - V_j(A_1) - p_j}{v_j - p_j} \\ V_j(A_2) - V_j(A_1) \ge v_j \Leftrightarrow d_j(A_1, A_2) = 1 \end{cases}.$$

The index of credibility $\delta_{A_1A_2}$ of the claim A_1 outranks A_2 is then formulated as:

$$\delta_{A_1A_2} = C_{A_1A_2} \prod_{j \in \bar{F}} \frac{1 - d_j(A_1, A_2)}{1 - C_{A_1A_2}}, \text{ with } \bar{F} = \{j \in F, d_j(A_1, A_2) > C_{A_1A_2}\}.$$

The claim A_1 outranks A_2 is rejected if v_j is exceeded for at least one of the criteria under consideration. After constructing the ranking scheme, as a last step, sensitivity analysis is activated, considering that values and assessments are often subjective in real-world cases and originate from less or more reliable estimations (criteria qualitative expression, threshold parameters, weighting factors, etc.). As already highlighted, this is considered a major advantage of the adopted MCDA technique due to the high data uncertainty in the thematic area under study [46].

2.3. Technology, Size, and Capacity of the UABT

The decision for the optimal site in the wider area presents a strong interrelationship with the determination of the technology to be adopted (Step 3b). A range of available technologies are available (e.g., anaerobic digestion, aerobic digestion, gasification, pyrolysis) and possibly a combination of these. The key factors that need to be considered for selecting the optimal technology are the potential for bioenergy production (electricity, heat or gas), possible utilization of the residues of each technological solution (e.g., biofertilizer), suitability of available bioresources, and pre-treatment requirements. All this information supports the optimal decision on technology for the UABT, based on constraints related to the type of biowaste and specific technological solutions used.

As a next step, the assessment of the size and capacity of the UABT is realized (Step 4), which is based on a cost-benefit analysis (CBA) and the determination of the biomass mixture for the UABT (range of sources depending on the biowaste quality). The latter ultimately leads to the dimensioning and detail of the technical specifications for the UABT. Highlighting strategies for risk management is the last step of the methodological roadmap presented (Step 5). The abovementioned methodological framework is expected to support policy-makers to facilitate the conceptual phase towards the development of a UABT, before advancing to the next phase of the planning phase where more resources are required. In this light, decision-makers may screen available options and give a green light for further analysis only to those cases where the endeavor is proven viable.

3. Application of Methodology in the Region of Serres, Greece

3.1. The Area under Study

The applicability of the methodological framework was validated in a real-life case study in the region of Serres, Greece. The region of Serres under study was pre-selected based on the considerable regional agricultural activity and biomass availability. The population of the wider Serres area is approximately 200,000, out of which 25% is urban, 20% semi-urban, and 55% rural/agricultural. Its economic activity mainly deals with the primary sector and especially with agriculture (approximately 60%). In the region, there are 162,800 ha of cultivated land and 113,300 ha of pasture land. More than 90% of the cultivated land is private. In the area, there is well-developed agricultural production, which contributes 3.4% of the total national agricultural product, with the main drivers being dairy and meat production. Apart from farmers, within a range of 20 km from the municipality of Serres, there are a number of agri-food manufacturers. Specifically, the relevant production activity consists of 2 leading dairy industries, 6 small cheese/yogurt production units, 2 olive mills, 1 potato packing and processing unit, 4 poultry farms, more than 30 cattle and pig rearing units for dairy and meat production, and one slaughterhouse.

These facilities are capable of supplying adequate quantities of biowaste to generate a mixture that ensures the continuous operation of a UABT. Considering the available data and given the population and basic economic activity characteristics of the wider area under study, a primary course of action regarding biowaste energy content could be supported by the recent legislative framework set in Greece regarding energy communities [47]. The legislation sets the rules for the incorporation of quasi-private entities with the option of participation of the municipalities as shareholders, while also providing the alternative of subsidized (or with tax-incentives) renewable energy plants. Such strategic schemes could also opt from the formation of public–private partnerships.

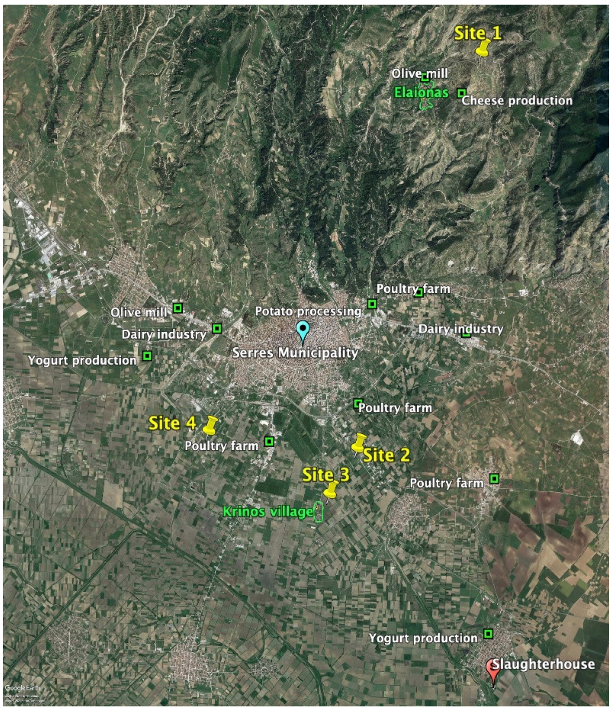
The region under study has great potential for the application of a productive UABT model due to many reasons, such as: (i) The availability of resources and biowaste, (ii) scientific potential and know-how, and (iii) the existence of a primary sector with growth potential and needs for modernization and reduction of production costs. Last, but not least, local farmers are strongly interested in adjusting their traditional economic attitudes. This high level of engagement was is result of intense awareness-raising activities (including flyers/brochures dissemination, press and media publicity, public presentations, visits to demonstration projects) as well as public opinion surveys that leaded to accurate expectation mapping of all involved local stakeholders [48].

3.2. Alternative Sites and MCDA

According to the methodology described, different locations for the development of the UABT within the area under study (Figure 1) were promoted. Following a detailed survey on land availability, four alternative available fields were selected, such as those sites are summarized in Table 1.

Next, the criteria for the analysis were defined in order to interlace financial viability, environmental performance, and acceptance by the local community, taking additionally into account all legislative constraints. A critical mass of local experts, also aware of the local special characteristics, were invited. In total, 13 experts representing local and regional authorities and the business sector in the study area were interviewed to decide on the criteria to be used in the case under study. This resulted in the following criteria: (Cr_1) Distance from biowaste source, (Cr_2) accessibility of the site with the existing infrastructure, (Cr_3) distance from units for the consumption of energy (electricity and heat) produced, (Cr_4) distance from farms for compost use, (Cr_5) value of land, (Cr_6) impacts on local populations (e.g., air pollution, odors, noise pollution), (Cr_7) impacts on local ecosystems, (Cr_8) aesthetic degradation, (Cr_9) increase in road traffic due to UATB's operation, and (Cr_{10}) social acceptance.

Table 1. Alternative locations for UABT development in the area under study.

Location of Sites	Site	Description
	Site 1	Located in a public area in Eleonas in the Forage Park. Access is through a forest road network with great difficulty. Road and water supply projects are required. Distance from the city is about 10 km and 23 km from the Slaughterhouse.
	Site 2	Located in a public area in the Farm of Serres, 2 km from Serres and 7 km from the Slaughterhouse. Access is easy via the "Serres-Neos Skopos" provincial road. A few meters from the site, there is a municipal vegetable garden and a greenhouse.
	Site 3	Located in a municipal area in the Farm of Serres, 0.5 km from Krinos village and 8 km from the Slaughterhouse (via dust road, or 12 km via municipal roads).
	Site 4	Located in a public area in the Farm of Serres, near the Omonia Sports Park. The site is 13.5 km from the Slaughterhouse via municipal roads and 0.5 km from the city.

The four site locations were assessed over their performances on the 10 designated criteria (Table 2). Criteria Cr$_2$, Cr$_6$, Cr$_7$, Cr$_8$, Cr$_9$, and Cr$_{10}$ were qualitatively assessed by the experts involved in the survey. Those criteria that are related to the distances (Cr$_1$, Cr$_3$, Cr$_4$) were assessed with the use of Google maps and the location of available biowaste sources and facilities where the outputs of the UABT could be exploited (farms and manufacturers) [48]. Cr$_5$, which is related to the value of the land, was assessed with mean objective values, which were provided by the Hellenic Statistical Authority. For all selected criteria, the higher the performance, the more preferable the alternative is assessed.

Table 2. Assessment of alternative site locations (*in 1–10 scale, where 10 is the most preferable*).

Criterion	Site 1 (1–10)	Site 2 (1–10)	Site 3 (1–10)	Site 4 (1–10)	Weights (%)	p_i	q_i
Cr$_1$ - Distance from biowaste source	1.46	8.92	6.92	5.69	15	1.87	0.56
Cr$_2$ - Accessibility of site	1.69	9.62	6.31	6.77	14	1.98	0.59
Cr$_3$ - Distance from units for energy consumption	2.00	9.46	7.54	7.15	12	1.87	0.56
Cr$_4$ - Distance from farms for compost use	3.85	9.23	8.31	7.69	8	1.35	0.40
Cr$_5$ - Value of land	2.85	9.15	7.62	7.23	12	1.58	0.47
Cr$_6$ - Impacts on local populations	9.23	7.31	2.62	2.00	10	1.81	0.54
Cr$_7$ - Impacts on local ecosystems	3.85	8.00	5.92	5.77	10	1.04	0.31
Cr$_8$ - Aesthetic degradation	4.85	8.46	4.69	3.23	6	1.31	0.39
Cr$_9$ - Increase in road traffic due to UATB	3.08	7.08	2.85	3.46	5	1.06	0.32
Cr$_{10}$ - Social acceptance	8.69	8.46	2.69	2.23	8	1.62	0.48

Weighting factors are also depicted in Table 2. Those were estimated as averages of the experts' views. In order to overcome subjectivity issues, sensitivity analysis was employed. In our case, a low computational time was required to re-calculate the optimal solutions with the modified parameters. The calculation of p_i (preference thresholds) for the selected criteria was based on the use of Equation (1) [44,46,49,50], while the calculation of q_i (indifference thresholds) was based on the use of Equation (2) [46,51]:

$$p_i = \frac{1}{n}(V_i max - V_i min), \tag{1}$$

$$q_i = 0.3 \cdot p_i \tag{2}$$

3.3. Technology, Size, and Capacity of the UABT

Based on the above analysis, a combination of anaerobic and aerobic digestion is promoted as the selected technological solution. Anaerobic digestion (AD) fits the local agricultural and farming well since manure, cheese whey, side products (i.e., rotten potato pulp, oil mill waste), and slaughterhouse waste are efficient substrates available in the area. AD is considered as the process where value is produced mainly for the generation of bioenergy (CHP) and biofertilizer. AD is a fermentation process, which is realized in an air-sealed biodigester (under conditions of oxygen absence). The feedstock (biowaste substrates) is converted into fuel gas and digestate (as a bio-product). The biogas that is produced comprises mainly of CH_4 (50%–70%) and CO_2 (30%–50%). Moreover, in smaller quantities, the biogas consists of H_2O vapor, H_2S, and other elements. The digestate is produced from the digestion of substrates, after biogas extraction. Wet digestate comprises of nutrients (e.g., nitrogen, lignin, phosphorous), inorganic salts (e.g., ammonium, phosphate, potassium), as well as other minerals. Therefore, it is suitable for use as a naturally derived fertilizer. In the literature, there are many studies related to the exploitation of AD [52–55]. Regional AD applications are also detailed in [56]. The substrates used determine the appropriate technical infrastructure that is required (e.g., pipes' sizing, pumps' specifications, gas storage requirements, gas treatment technology, and Combined Heat and Power - CHP design).

The technology adopted does not add to the CO_2 load in the atmosphere, since the CO_2 produced is offset by the prevented emissions of CH_4 in the case that slurry is stored in open spaces. In this light, biogas can significantly contribute to decarbonization of the economy. Furthermore, decentralized bioenergy generation from biofuel in UABTs with CHP is becoming more attractive for the cases where generated heat is exploited in facilities within the proximity of the UABT. Moreover, the use of UABTs' end-products (energy and bioproducts) needs to be meticulously examined within the pre-planning phase. In this context, the use of the produced bio-fertilizer in farms close to the developed UABTs highly supports their financial performance and effectiveness. The sufficiency of arable land for spreading available biofertilizer and an available adjacent market for the digestate needs to be investigated. In addition, biofertilizers' nutrients are predominately contained in a mineral form, which allows ease of absorption by plants and increased uptake efficiency, in comparison to nutrients in raw manure or in slurry [57].

Based on the above, it is proven in practice by the operation of such multi-functional facilities that this technology offers reduced local community energy costs, low-cost and environmentally safe recycling of manure and biowaste, cheap and efficient crop biofertilization means, and a reduction of odors due to intensive farming activity. Thus, considering also that in many areas, organic substances are still disposed in landfills (contributing to local CH_4 emissions), the proposed UABT apparently dually contributes towards global warming mitigation through (a) the decreased CH_4 emissions in animal farms (due to digestate management and avoidance of open slurry storage), and (b) the production of a green decarbonized (bio-)fuel. Along with the latter, improved digestate nutrient management, in combination with sustainable agri-practices [58], has a positive effect on the reduction of NH_3 and NO_x emissions, as well as the eutrophication of surface and ground water since leakages can be decreased or even avoided. Furthermore, local eutrophication is also achieved through biogas treatment of manure [59].

4. Results and Discussion

4.1. Feedstock

Based on the inventory analysis, the UABT receives organic biowaste types. More specifically, Table 3 presents the results of the annual received quantity of each substrate, their supply (d/a), and the quantity of each substrate per day of supply [48]. The codification of each substrate is presented in accordance with the European Waste List (EWL) (as per Annex to Decision 2000/532/EC).

Table 3. Substrate mix composition, yearly supply schedule, and yearly supply quantities.

Raw Material	Supply Quantity (Tons/Day)	Days of Supply (Days/Year)	Overall Quantity (Tons/Year)	EWL Code
Dairy cow slurry manure	6.27	200	1254	02 01 06
Cow manure	5.91	200	1183	02 01 06
Calf manure	0.51	200	102	02 01 06
Cattle manure	0.73	200	146	02 01 06
Poultry manure	0.32	104	33	02 01 06
Cheese whey	1.78	156	278	02 05 01
Rotten potato pulp	1.00	32	32	02 01 03
Olive mill waste	2.37	32	76	02 03 01
Slaughterhouse waste - Intestine content	1.44	104	150	02 02 01
Slaughterhouse waste - Stomachs and fat	0.25	52	13	02 02 02
Slaughterhouse waste - Blood	0.35	52	18	02 02 02
		TOTAL	**3285**	

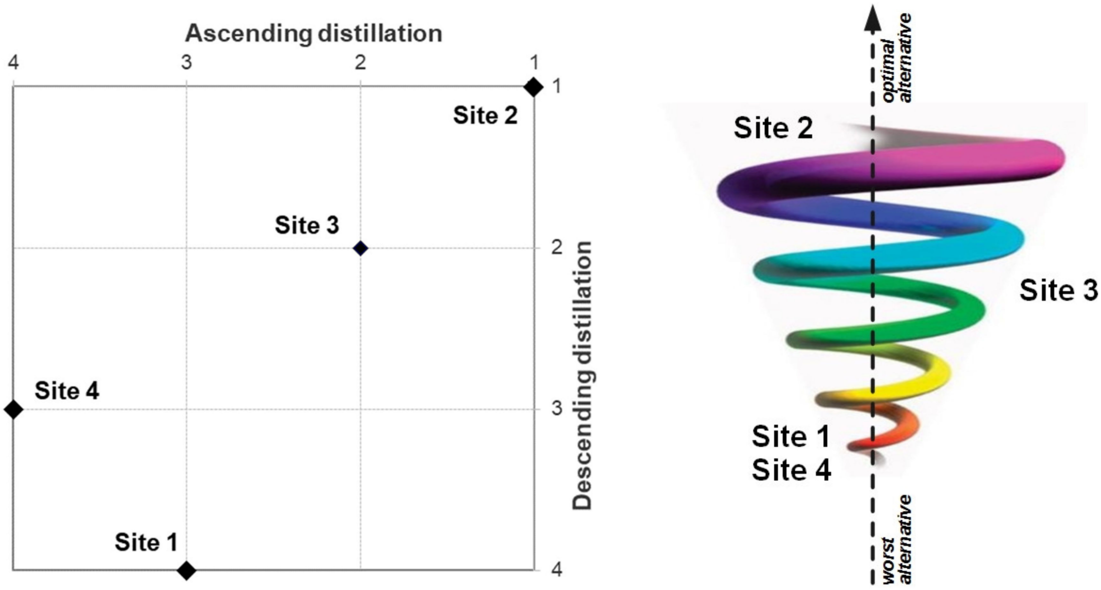
The energy density of manure is considerably low, mainly due to the high content in water, along with the relatively low gas yield. The latter decreases its attractiveness for the case of long transportation distances. On the other hand, hydraulically, slurry is comparatively easy to handle. In the cases where the proportion of manure is relatively high within the digester, substrates like grass or solid manure, which are usually hydraulically more demanding, show a good performance in a small-sized biogas plant.

4.2. Optimal Site

The use of ELECTRE III in the case herein examined was realized with LAMSADE software. The two distillations (ascending and descending) that result from the analysis of the sites' performances are graphically displayed in Figure 2a. Both ascending and descending distillations promote Site 2 as the optimal alternative for the UABT's location. This is also displayed in Figure 2b, where the four alternatives ae hierarchically ranked. Site 2 (optimal location) is approximately 1.5 km south-southwest of the city of Serres, within municipality-owned land of approximately 16 acres.

As presented in Figure 2b, site 2 is judged as the optimal location locally. The latter is grounded on its outstanding assessment in most of the examined criteria (Table 2). This is well-justified due to the fact that site 2 is in the proximity of major producers of high-value biomass and potential end-users of the produced energy. Due to the fact that the area is industrial, the infrastructure in the proximity of site 2 is in very good condition, while the specific site also shows a very good performance in the social criteria (impacts on local populations and ecosystems, aesthetic degradation, increase in road traffic, social acceptance).

As a next step, a sensitivity analysis was conducted. The thresholds in the mathematical formulation (preference and indifference) were modified, as presented in Table 4. More specifically, six scenarios were examined. The optimal location for the development of the UABT in the region of Serres is site 2 for all examined scenarios. The latter increases the robustness of the basic solution and provides confidence in relation to the efficiency of the location over other available alternatives.



(**a**) (**b**)

Figure 2. Optimal UABT location: (**a**) Ascending and descending distillations - (**b**) Ranking of alternative locations.

Table 4. Sensitivity analysis.

Thresholds	**Scenario**						
	Baseline	**A**	**B**	**C**	**D**	**E**	**F**
$\mathbf{p_i}$	p_i	$1.25 \times p_i$	$1.50 \times p_i$	$0.75 \times p_i$	$0.50 \times p_i$	p_i	$0.50 \times p_i$
$\mathbf{q_i}$	$0.3 \times p_i$	$0.375 \times p_i$	$0.45 \times p_i$	$0.225 \times p_i$	$0.15 \times p_i$	0	$0.30 \times p_i$
Variation	-	+25%	+50%	−25%	−50%	$p_i = p_i \mid q_i = 0$	$p_i = \frac{1}{2}\, p_i \mid q_i = 0$
Ranking	**1st: Site 2** 2nd: Site 3 3rd: Site 1,4	**1st: Site 2** 2nd: Site 3,4 4th: Site 1	**1st: Site 2** 2nd: Site 3,4 4th: Site 1	**1st: Site 2** 2nd: Site 3 3rd: Site 1,4	**1st: Site 2** 2nd: Site 3 3rd: Site 1,4	**1st: Site 2** 2nd: Site 3 3rd: Site 1,4	**1st: Site 2** 2nd: Site 3 3rd: Site 1,4

4.3. Technical Specifications

The biowaste is collected from the production and disposal sites and transported by container trucks and/or simple trucks to the UABT. Biowaste is introduced into the reception tanks to be mixed through agitation and formulate the final substrates' mix for AD. The mix is pumped and transferred (via the displacement pumps) to the digesters. The UABT will produce approximately 160,000 m^3 of biofuel per year. The biogas is collected and transferred to the internal combustion engine (ICE) for the production of electrical and thermal energy. The estimated electricity generation amounts to 311,996 kWh/a of operation, including self-consumption needs and grid losses. The estimated thermal bioenergy generation is 356,216 kWh/a, including thermal losses and self-thermal energy consumption. More specifically, the excess electrical energy is fed to the low voltage grid and its selling price offsets the electricity purchase costs of the municipality of Serres. The excess thermal energy serves the heating needs of a greenhouse adjacent to the unit's site and is partially used to heat the substrates' mix inside the biodigesters through a shell-type heat exchanger. This conducts the heat from the ICE's exhaust gases to the closed hot water circuit passing through the digesters. At the closed hot water circuit's return, the water, at a lower temperature than that when coming out of the shell-type heat exchanger, is pre-heated with the use of a heat exchanger (plate-type) and simultaneously cools the ICE, before passing through the shell-type heat exchanger again and increasing its temperature from the exhaust gases of the ICE.

The above process was calculated to produce 3121 t of aqueous residue, rich in nutrients for deposition in cultivations adjacent to the UABT. The proposed AD process is thermophilic. The biowaste mixture remains inside the digesters for at least 20 days (hydraulic retention time ≥ 20 days) at a temperature of at least 52 °C. The digestate is pumped in a controlled manner and transported to the screw separator, which recovers its solid fraction to be bagged, while the liquid fraction is placed in a lagoon. The solid fraction bags are picked up by trucks and the liquid fraction is pumped and transported by tank containers, both to be deposited in adjacent crops during eligible fertilization periods.

It should be emphasized that the application of biofertilizer needs to be realized in the growth season for any given crop. This is necessary in order to increase the uptake of nutrients, as well as to avoid a leaching or surplus of nutrients. Apart from the nutrient content, a fertilizer needs to also show high quality in sanitation and the reduction of pathogens; quantities of organic compounds and heavy metals, plastic, or other contaminants; etc.

The proposed methodology's clear strength lies on the multi-functionality of this technological solution. UABTs' sustainability can be grounded on many different aspects, such as (a) exploitation of organic waste, (b) upgraded management of manure, (c) increased uptake efficiency of nutrients, (d) reduced odors, (e) protection of the environment and reduced GHG emissions, (f) increase of material value, and (g) bioenergy (in the form of electricity and heat) and biofuel production.

5. Conclusions

In our work, we proposed a methodological scheme aimed towards supporting decision-makers in assessing the development of a UABT, based also on multiple criteria and factors. The methodology was effectively validated in a real-world case study in the region of Serres, Greece. In the approach proposed, the decision for the optimal location of the UABT within the area under study was based on the results of a multicriteria analysis (with the use of ELECTRE III technique), taking into consideration qualitative and quantitative criteria. In the case presented, the optimal site for the location of the UABT results from its excellent performance in the selected criteria, which represent all pillars of sustainable development, namely financial viability, public acceptability, and environmental protection.

The proposed methodological scheme provides a roadmap either for public bodies or private companies that aim to invest in green energy projects. The methodology followed in this work is generic so as to be followed under different requirements and constraints in any real such investment, with slight modifications of the criteria or values in the thresholds and weighting factors according to the special conditions in the area under study. The methodological framework can also be used to make decisions on other issues related to the supply chain management, namely the optimal location of collection sites, warehousing, sorting centers, etc., after relevant modifications in the criteria considered.

Even though the production of biogas has been widely realized over the past decades, the large-scale substitution of fossil fuels is still considered a major innovation in the energy sector. Energy technologies that exploit biomass for energy production are still non-competitive and technologically inefficient and immature against the conventional use of non-renewable sources. The methodology presented provides a little stepping stone towards supporting a bioeconomy within the field of clean technology biowaste and residues, within the concept of a circular economy, which is currently in its advent. It should be emphasized that such AD technological solutions are followed by challenges that limit the wider applicability, i.e., (i) the lack of markets for the digestate produced resulting from poor public perception; (ii) lack of recognition of AD and composting, especially regarding nutrient recirculation; (iii) purity of segregated biowaste streams; and (iv) requirements in capital investment.

Author Contributions: Conceptualization, methodology and paper writing, C.V.; Conceptualization, graphical illustration and validation of results C.A.; AD-related data, I.A.; Software runs and sensitivity analysis, A.V.M.; Case study related data, C.P.; Literature review, E.F.; Structure formulation, N.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the INTERREG IPA Cross Border Cooperation Programme CCI 2014 TC 16 I5CB 009 grant number SC032 (ZEFFIROS project).

Acknowledgments: The authors would like to wholeheartedly thank the experts that participated to the MCDA application in the study area.

Conflicts of Interest: The authors declare no conflict of interest.

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