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A Multi-Criteria Assessment of Energy Crops for Biogas Production

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This paper presents the system for the assessment of energy crops for biogas production. The system is based on simulation modelling and multi criteria decision analysis. The deterministic simulation system consists of deterministic production simulation models that enable different types of costs calculations for the production of energy crops, electrical and heat energy in biogas production. Simulation model results were further evaluated using a qualitative multi-attribute modelling methodology (supported by the software tool DEX-i) and quantitative analytical hierarchical process – AHP (supported by the software tool Expert Choice 2000^{TM}). The analysis showed that by using current model the most relevant alternative used for energy crop for biogas production is maize. The maize results in the best multicriteria evaluation EC = 0.248 and DEX-i evaluation = appropriate. The best alternative for maize is sorghum with multicriteria evaluation of EC = 0.201 and DEX-i evaluation = less appropriate.

Keywords: simulation model, Expert Choice (AHP), DEX – i, energy crops, biogas

0 INTRODUCTION

The world in the 21st century is faced with problems due to growing energy consumption and diminishing supplies of fossil fuels, which has led to research on the use of renewable energy sources and, consequently, the development of new technological processes of energy production. One of the most efficient energy sources is the biogas produced from green energy crops and organic waste matters. Economic efficiency of anaerobic digestion depends on investment costs, costs of operating the biogas plant and on the optimum methane production. The biogas is a renewable source of energy and reduces CO_2 emissions. The biogas has a very positive impact on the environment since less CO_2 is formed during its combustion than it is used for photosynthesis by the plants from which it is produced [1] and [2]. The biogas is formed during anaerobic fermentation of organic matters such as: farmyard manure, liquid manure, energy crops, organic waste materials, slaughter-house waste and similarly.

From the technological aspect the most suitable energy crops grown in the temperate conditions are the grasses [3] and [4], maize, sorghum and legumes such as white clover, vetches and lupine [5] and [6]. Among alternative energy crops literature mentions the forage kale, Jerusalem artichoke, Miscanthus sp. and some weeds [7].

For the purpose of planning and decision-making regarding the use of different substrates (energy crops, biomass) in the biogas plant, economic information is required besides technological information. Model calculations of energy crops production costs represent a sufficient high-quality information support for the development of further studies [8] and [9]. A wide variety of simulation models are built by agricultural economists on the development of systems to support decision-making in combination with multi-criteria decision analysis [9] and [10, 23, 24].

The basic problem of the research is to develop a system to support decision-making in the selection of the appropriate energy crop, with the combination of the technological-economic simulation model (model calculations) and multi-criteria decision analysis. The relationship between technological-economic simulation models and multi-criteria decision analysis to support the planning of production is a new approach to developing systems to support decision making in agricultural management [8].

An important issue is evaluating the suitability of energy crops for biogas with respect

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to various criteria on the basis of different analyses (amount of produced biogas, biomass yield) and the association in a single multi-criteria estimate. In such cases, the multi-criteria analyses were used by different authors [8] to [11].

This paper presents an application of the simulation model for the cost analysis of biogas, electricity and heat production from various energy crops in combination with multi criteria decision models. The simulation results are additionally evaluated with multi criteria decision models based on AHP methodology (Expert Choice): Expert Choice decision support system (AHP) and DEX-i expert system.

1 METHODOLOGY

For a financial and technological analysis of energy crops for biogas production the computer simulation model was developed. Using technological-economic simulation modelling information about the system itself and its responses to different model input parameters can be obtained. The relationships between system elements (in this case input material, human labor) are expressed with a series of technological equations that are used for the calculation of input usage and outputs produced. There are three basic sub-models: the sub model of energy crop production by the farmer, the sub model of biogas production from energy crops and the sub model of electricity and heat production from biogas produced from energy crops. The developed model enables a calculation of the most important economic parameters such as break-even price, coefficient of profitability and financial result. The simulation model output data represent some of the input parameter of the analyzed energy crops in multi-criteria decision analysis. The structure of the assessment procedure is shown in Fig. 1.

The detailed description of the biogas simulation model is given in [12]. The model input data are provided by laboratory measurements as described in [13].

The energy crops are further evaluated with multi criteria decision model. Hierarchical multi-criteria decision models are a general decision support methodology aimed at the classification or evaluation of options that occur in decision-making processes [12]. Decision models are typically developed through the decomposition of complex decision problems into smaller and less complex sub-problems; the result of such decomposition is a hierarchical structure that consists of attributes and utility functions.

The multi-criteria model is a hierarchical structure that represents a decomposition of the decision problem into sub-problems, which are smaller, less complex and possibly easier to solve than the complete model. Fig. 2 shows the hierarchy of energy crop assessment problem.

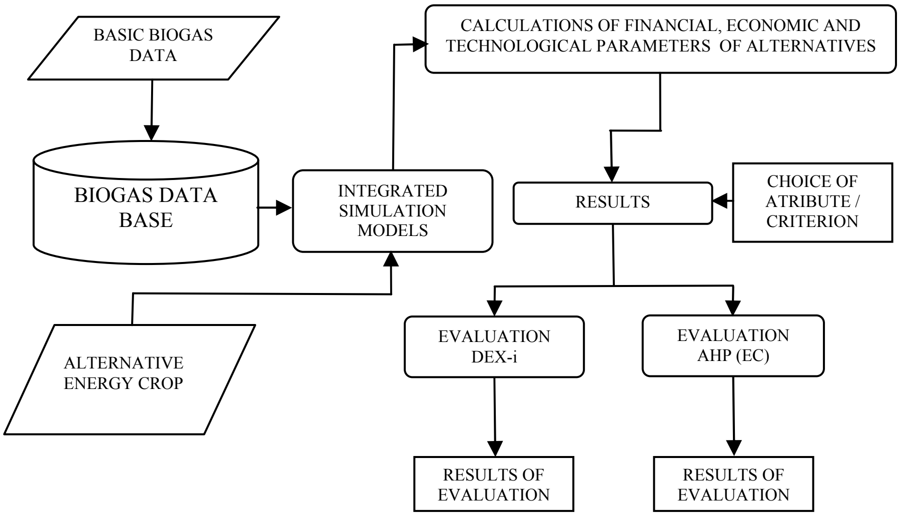

Fig. 1. *The structure of deterministic simulation model for calculations and energy crops for biogas production*

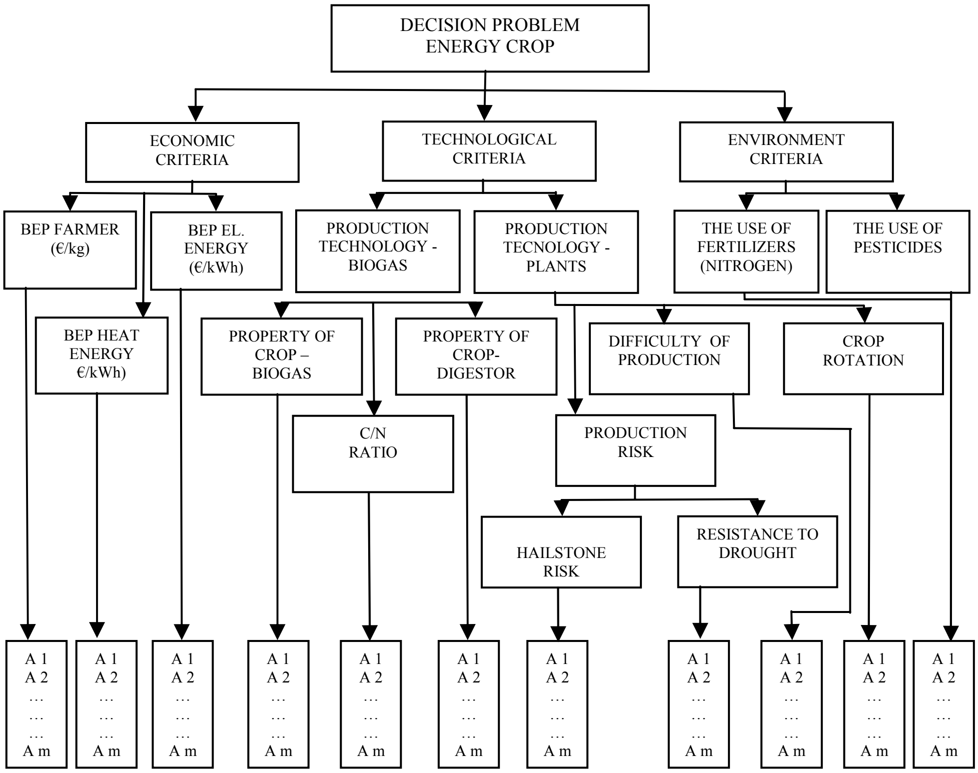

Fig. 2. *The hierarchy of assessment problem energy crop*

The variants are decomposed into specific parameters (criteria, attribute and objective) and evaluated separately for each single parameter. The final variant evolution is provided with the combined proceeding. The provided value presents the portfolio for selection of the most suitable variant [14]. For the assessment of simulated alternatives two methodologies have been applied: DEX-i method and AHP based Expert Choice (EC).

1.1 The DEX-i Assessment

DEX is a methodology for qualitative multi-criteria decision modelling and support [15]. DEX combines conventional multi-criteria decision-making with some elements of Expert Systems and Machine Learning. A distinguishing characteristic of DEX is its capability to deal with qualitative variables. Instead of numerical variables, which typically constitute traditional quantitative models, DEX uses qualitative variables whose values are usually represented by words rather than numbers, such as ‘‘low,’’ ‘‘appropriate,’’ and ‘‘unacceptable.’’ To represent and evaluate decision alternatives, DEX uses ‘if-then’ decision rules. The DEX method is implemented with the software program DEX-i [16]. To date, the method has been applied to numerous real-life decision problems [17] to [19] and [21] to [22].

The DEX-i decision model is developed by defining:

- attributes (qualitative variables that represent decision sub-problems),
- tree of attributes (a hierarchical structure of the decision problem),
- utility functions (rules that define the aggregation of attributes),
- alternative evaluation.

The numerical attributes for the DEX-i analysis were obtained by simulation using the simulation model, while the non-numerical attributes were estimated based on different data sources. The following qualitative scales were used for non-numerical sub-attributes (Table 1).

After each attribute has been assigned with qualitative value, the utility functions are defined. The utility function is conducted for each level in the hierarchy and the decision rules are presented in complex form. Table 2 shows qualitative scales for non-numerical attributes.

Table 1. *Categorization table for numerically measured attributes*

The use of fertilizers (nitrogen)	Qualitative values
>195	high
131 - 194	medium
0-130	low
BEP farmer [€/kg]	
< 0.08	high
0.035 – 0.08	medium
> 0.035	low
BEP el. energy [€/kWh]	
< 0.4	high
0.2 – 0.4	medium
> 0.2	low
BEP heat energy [€/kWh]	
< 0.2	high
0.11 – 0.2	medium
> 0.1	low
C/N ratio [carbon/nitrogen ration]	
15-30/1	optimum
>< 15-30/1	less appropriate

Finally, attribute values for each alternative are put into DEX-i evaluation table and the analysis is ultimately conducted.

Table 2. *Qualitative scales for non-numerical attributes*

Hailstone risk	high; medium; low
Resistance to drought	resistant; partially resistant; un-resistant
Crop rotation	monoculture; two years; three years
The use of pesticides	high; medium; non
Insistence of the production	high; medium; low
Suitability of plant for processing into biogas	appropriate; less appropriate; inappropriate
Suitability of plant - digestor	appropriate; less appropriate; inappropriate

1.2 Multi-criteria Modelling Methodology Analytical Hierarchical Process

The analytical hierarchy process (AHP) developed by Saaty [11] is a multicriteria decision-making technique which decomposes a complex problem into a hierarchy, in which each level is composed of specific elements. The AHP is supported with software Expert Choice 2000^{TM}. The overall objective of the decision lies at the top of the hierarchy, and the criteria, sub-criteria and decision alternatives are at the descending levels of this hierarchy. The hierarchy does not need to be complete, i.e. an element in a given level does not have to function as a criterion for all the elements in the level below. A hierarchy can thus, be divided into sub-hierarchies sharing only a common topmost element.

Once the hierarchical model has been structured for the problem, the participating decision makers provide pair wise comparisons for each level of the hierarchy, in order to obtain the weight factor of each element at that level with respect to one element in the next higher level. This weight factor provides a measure of the relative importance of this element for the decision maker.

To compute the weight factors of *n* elements, the input consists of comparing each pair of the elements using the following scale set:

$$\mathrm{S} = \left\{\frac{1}{9},\frac{1}{8},\frac{1}{7},\frac{1}{6},\frac{1}{5},\frac{1}{4},\frac{1}{3},\frac{1}{2},1,2,3,4,5,6,7,8,9\right\} \tag{12}$$

The pair-wise comparison of element *i* with element *j* is placed in the position of a_{ij} of the pairwise comparison matrix A as shown below:

$$\mathrm{A} = \begin{pmatrix} a_{11} & a_{12} & a_{1n} \\ a_{21} & a_{22}\cdots & a_{2n} \\ \vdots & \ddots & \vdots \\ a_{n1} & a_{2n}\cdots & a_{nn} \end{pmatrix} \tag{2}$$

The following steps for applying AHP were developed [11]:

1. Define the problem and determine its goal.
2. Structure the hierarchy from the top through the intermediate levels to the lowest level which usually contains the list of alternatives.
3. Construct a set of pair-wise comparison matrices for each of the lower levels with one

matrix for each element in the level immediately above by using the relative scale measurement.

4. There are n x (n-1) judgments required to develop the set of matrices in step 3.

5. Hierarchical synthesis is now used to weight the eigenvectors by the weights of the criteria and the sum is taken over all weighted eigenvector entries corresponding to those in the next lower level of the hierarchy.

6. Having made all the pair-wise comparisons, the consistency is determined by using the eigenvalue, λ_{max}, to calculate the consistency index, CI as follows: $CI = (\lambda_{max} - n)/(n - 1)$, where n is the matrix size. Judgment consistency can be checked by taking the consistency ratio (CR) of CI. The CI is acceptable, if it does not exceed 0.10.

The EC software allows the data for each alternative to be entered into the so called Data Grid, where individual objectives can be entered directly. The intensities or possible qualitative values of decision attributes at the lowest level in the hierarchy are compared in the pair-wise comparison matrix. The same qualitative scales as in the DEX-i model can be used for qualitative attributes. The data are entered for each alternative. Priorities of alternatives are established relatively to each covering objective by using ratio scaled rating intensities (scales).

Six alternatives (energy crops maize, sorghum, amaranth, sugar beet, Jerusalem artichoke and sunflower) were considered to apply the simulation model and MCDA methods using the presented methodological approach.

First, the mini digester consisting of twelve units was built and then some measurements with energy crops were performed. The mini digester for biogas production was built according to DIN 38414, part 8 [20]. Whole energy crops in certain ratio were anaerobically digested and biogas yields and biogas composition were measured and compared. Energy crops were chopped after harvest and then mixed in certain ratios, prior to the ensiling process. The particle size was 2.0 to 4.0 mm. Substrates were analysed prior to digestion for pH, dry matter, crude protein, crude fibre, starch, crude fat, ash and *C/N* ratio with standard analysing procedures.

2 RESULTS AND DISCUSSION

In the first phase for every analyzed alternative the costs of energy crop production are calculated using the simulation model. In the second phase, the data from the experiment (produced biogas) were calculated into the electricity and heat yield. Table 3 shows the results of the simulation model for the individual alternative.

The simulation results were further evaluated with multi criteria decision model DEX-i and AHP. Since the main results from the simulation model are numerical (break even prices, *C/N* ratio), the qualitative values must be assigned to each quantitative parameter in order to enable further analysis in DEX-i decision model. This is conducted with classification algorithm based on classification intervals.

The DEX-i evaluation of alternatives (energy crops) with importance weights of aggregate attributes is shown in Table 4. Table 5 shows the AHP evaluation of alternatives.

Table 3. *The results of biogas production measurements and simulation model for individual energy crop*

	Biogas [Nl/kgVS][a]	Biogas [Nm^3/ha][b]	El. energy [kWh/ha]	Heat energy [kWh/ha]	BEP[c] farmer [€/kg]	BEP[c] el. energy [€/kWh]	BEP[c] h. energy [€/kWh]	C/N ratio
Maize	576	10332.5	20665	37197	0.026	0.18	0.10	1:24
Sorghum	509	7783.5	15567	28020	0.029	0.23	0.13	1:30
Amaranth	421	3641.4	7283	13109	0.782	0.51	0.28	1:14
Sunflower	495	5749.6	11499	20698	0.329	0.28	0.16	1:40
Jerusalem artichoke	463	5104.8	10210	18377	0.079	0.40	0.22	1:42
Sugar beet	649	5823.3	11647	20964	0.038	0.34	0.19	1:33

[a] norm litre per kg of volatile solids (273 K, 1.013 bar)

[b] norm m^3 per hectare

[c] break even price

Table 4. *DEX-i project evaluation of alternatives with importance weights of aggregate attributes*

Attribute	**Sunflower**	**J. artichoke**	**Sorghum**	**Sugar beet**	**Amaranth**	**Maize**
Assessment	less appropriate	inappropriate	less appropriate	less appropriate	inappropriate	appropriate
Economic criteria**W*=55%**	good	bad	good	good	bad	excellent
BEP farmer	high	medium	low	medium	high	low
BEP el. energy	medium	high	medium	medium	high	low
BEP heat energy	medium	high	medium	medium	high	low
Technological criteria ****W*=29%	bad	bad	good	bad	bad	good
Production technology - biogas	demanding	demanding	non demanding	demanding	non demanding	non demanding
Property of crop-biogas	less appropriate	less appropriate	appropriate	inappropriate	less appropriate	appropriate
Property of crop-digestor	less appropriate	inappropriate	appropriate	inappropriate	appropriate	appropriate
C/N ratio	less appropriate	less appropriate	optimum	less appropriate	optimum	optimum
Production technology-plants	demanding	middle demanding	middle demanding	demanding	middle demanding	middle demanding
Difficulty of production	medium	low	medium	high	low	medium
Crop rotation	three years	three years	two years	three years	two years	two years
Production risk	high	medium	medium	medium	medium	medium
Hailstone risk	high	medium	high	low	medium	high
Resistance to drought	un-resistant	partially resistant	resistant	un-resistant	partially resistant	partially resistant
Environment criteria**W*=29%**	good	good	bad	bad	bad	neutral
The use of fertilizers (nitrogen)	low	low	high	high	high	medium
The use of pesticides	medium	non	medium	high	medium	medium
Ranking	**2**	**3**	**2**	**2**	**3**	**1**

* Weights

Table 5. *The Expert Choice AHP alternatives evaluation for the sample of energy crops*

	Economic criteria	**Technological criteria**	**Environment criteria**		**Ranking**
Weight (W^a)	0.540	0.297	0.163		
	a^b			$\sum Wa^c$	
Maize	0.283	0.228	0.169	0.248	1
Sorghum	0.207	0.230	0.126	0.201	2
Sugar beet	0.170	0.082	0.209	0.150	4
J. artichoke	0.113	0.128	0.145	1.123	6
Sunflower	0.141	0.128	0.226	0.151	3
Amaranth	0.085	0.194	0.126	0.124	5

W^a – weight; a^b – alternative priority with respect to current node; $\sum Wa^c$ – alternative priority with respect to goal.

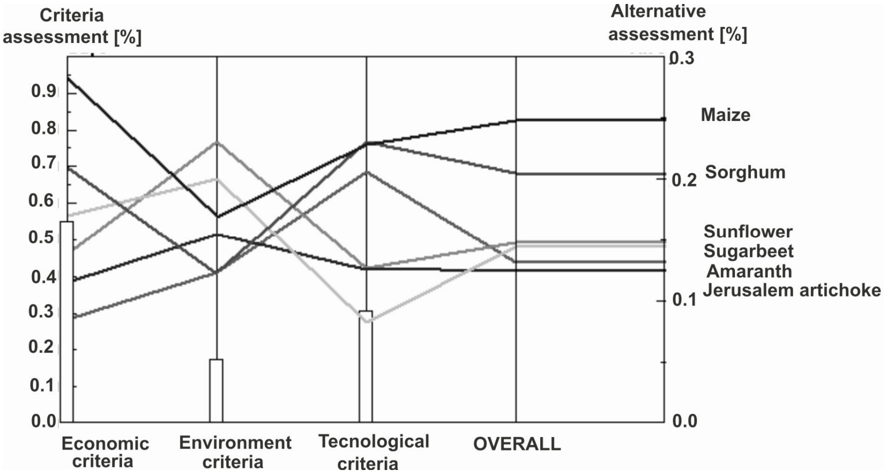

Fig. 3. *AHP assessment of energy crops with respect to three main criteria*

The DEX-i and AHP evaluation of alternatives in principle results in the same ranking of alternatives (maize, sorghum, sunflower, sugar beet, amaranth and Jerusalem artichoke). However, the AHP produces a more detailed ranking which can be useful when the alternatives are close to each other and would probably produce the same qualitative DEX-i evolution. Therefore, the applied AHP methodology should bring unequivocal clarity to the decision on which alternative should be used for biogas production with respect to different criteria (Table 5). The AHP does not exclude any alternatives, it only ranks them according to the defined hierarchy and relative importance of decision criteria. On the contrary, by using DEX-i expert system it can be defined which combination of attribute values is not acceptable for the decision maker. Thus, the DEX-i assessment can be used to exclude unacceptable alternatives. However, the shortcoming of DEX-i is its inability to separate between alternatives with the same qualitative evaluation.

Fig. 3 shows AHP assessment of energy crops with respect to three main criteria (economic, environment and technological).

3 CONCLUSIONS

In this paper, an attempt to employ multi-criteria analysis to assess suitability of energy crops for processing into biogas has been made.

The integrated simulation model combined with multi criteria decision analysis presents a suitable methodology tool for decision support system on farms and biogas plants. The system takes into consideration different independent criteria and enables the ranking of alternatives (energy crops). The use of both multi criteria decision approaches can bring additional information into the decision making framework (for instance the unacceptable alternatives can be excluded with the use of the DEX-i model, while the precise ranking of remaining alternatives is based strictly on the AHP Expert Choice model).

In the presented paper both methods (DEX-i and AHP) favoured the maize, which got the highest DEX-i and AHP evaluation. The maize is followed by sorghum and can be used as an alternative for maize (crop rotation, drought etc.). The next alternatives are sunflower, sugar beet, amaranth, while Jerusalem artichoke got the worst evaluation.

The application of the proposed decision support system (a combination of simulation model, AHP and DEX-i) would increase the accuracy of information needed for developing farm and biogas plant plans. In addition, it would help preventing many inappropriate decision being made on farms and biogas plants.

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