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Original Research

Evaluation of Energy Crops for Biogas Production with a Combination of Simulation Modeling and Dex-i Multicriteria Method

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Abstract

Our paper presents the system for multi-criteria evaluation of energy crops for biogas production. First, a deterministic simulation system consisting of deterministic production simulation models was built. Simulation model results were further evaluated using a qualitative multi-attribute modeling methodology DEX (supported by the software tool DEX-i). Analysis showed that by using the current model the most relevant alternative crop for biogas production is maize. Maize results in the best DEX-i multicriteria evaluation appropriate. The best alternatives for maize are sorghum, sunflower, and sugar beet, with multicriteria evaluation being less appropriate.

Keywords: multicriteria decision analysis, simulation model, DEX-i, energy crops

Introduction

World energy consumption in the 21st century is growing and supplies of fossil fuels are diminishing, which has led to researches of 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 [1]. The biogas is formed during anaerobic digestion of organic matters such as farmyard manure, liquid manure, energy crops, organic waste materials, slaughterhouse waste, etc. [1]. One of the most important parameters in biogas production is economic efficiency of anaerobic digestion, which depends on investment costs, on the costs for operating the biogas plant, and on optimum methane production [2].

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

An important issue is evaluating the suitability of energy crops for biogas production with respect to various criteria on the basis of different analyses (amount of produced biogas, biomass yield) and association in a single multi-criteria estimate. In such cases, the multi-criteria analyses were used by different authors [5, 6]. In the last few decades, the agricultural decision makers have gotten accustomed to the use of computers, and consequently, to the implementation of different complex computer models for solution of various planning problems. This includes decision problems and agricultural project solutions that have long been predominated by different types of simulation models [7] and cost benefit analysis (CBA) as presented by [8].

The basic problem of the research is to develop a system to support decision making in the selection of an appro-

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priate energy crop for biogas production, with the combination of the technological-economic simulation model (model calculations) and multi-criteria decision analysis. This paper presents the application of the simulation model for 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 the DEX-i expert system.

In our study, six energy crops were analyzed: maize, sorghum, amaranth, sunflower, sugar beet, and Jerusalem artichoke. These crops were chosen because they are quite dominant in Slovenian crop rotation, produce a lot of biomass, and have big growing potentials in this climate. The main attributes considered in the analysis are economic, technological, and environmental criteria for the selection of appropriate energy crops for biogas production.

Methodology

This study is based on simulation modeling and multi-criteria decision analysis. Simulation modeling combined with hierarchical multi-criteria decision models (MCDM) are a general decision support methodology aimed at the classification or evaluation of options that occur in decision-making processes [9]. 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 (Fig. 1) that consists of attributes and utility functions [10]. Typically, an application of MCDM involves two main stages:

(1) model development

(2) model application for the evaluation, assessment, and analysis of decision alternatives.

Our study closely follows this pattern. We first developed a qualitative multi-criteria decision model using the DEX methodology and then applied it to assess six energy crops.

Multi-Criteria Modeling Methodology DEX

DEX is a methodology for qualitative multi-criteria decision modeling and support [11]. DEX combines traditional multi-criteria decision-making with some elements of expert systems and machine learning. The 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." Furthermore, to represent and evaluate decision alternatives, DEX uses 'if-then' decision rules. For instance, a decision rule can be: "if the net present value is negative, then the alternative is not acceptable" or "if labor usage in the investment project is low, then the alternative is excellent." This is in contrast with the more common quantitative MCDA, which uses utility functions that employ weights, such as the expected value or weighted sum.

The DEX method is implemented with the software program DEXi [12]. To date, the method has been applied to numerous real-life decision problems [13-16].

The DEXi model is typically constructed through the following stages [17]:

1. The decision problem is hierarchically decomposed into less complex individual problems. The decomposition yields a tree of attributes (Fig. 1) that represents the hierarchical "skeleton" of the model. Terminal nodes ("leaves") of the tree represent inputs to the model, and the root node represents the main output: overall assessment of evaluated alternatives (in our case, energy crops).
2. Each sub-problem is represented by a qualitative attribute with a defined value scale. The value scale is discrete and typically consists of words (Fig. 2). In principle, the scale can be preferentially ordered (from 'bad' to 'good' values) or unordered. In Table 1, all scales are ordered.
3. Utility functions for each aggregate attribute are defined. In DEX, utility functions are represented by

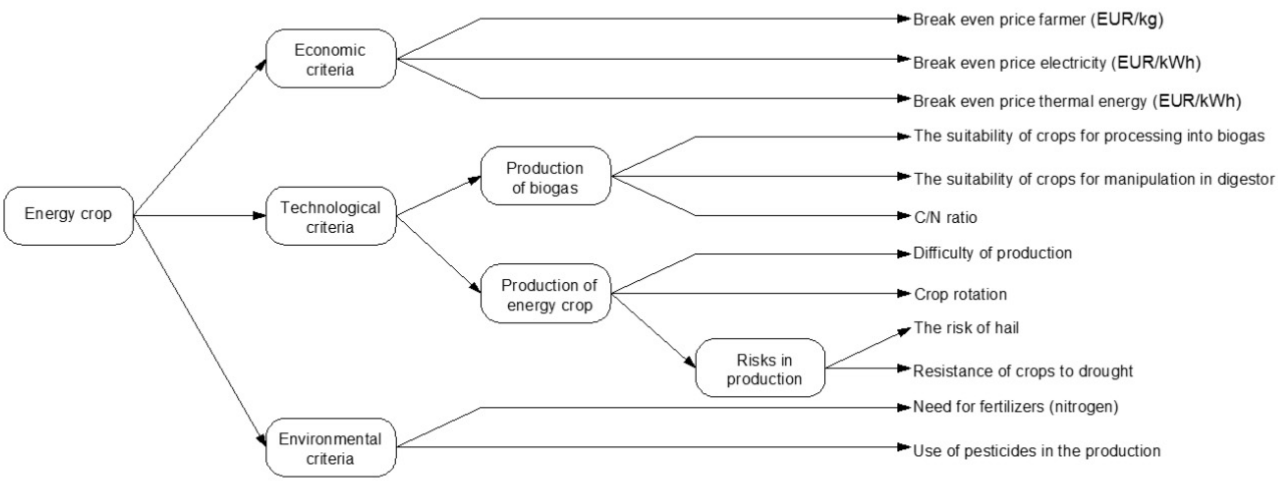

Fig. 1. Tree of attributes.

Table 1. Example of decision rules for the assessment of energy crops for biogas production. The rules map qualitative values of economic, technological, and environmental criteria into the attribute energy crop.

	Economic criteria	Technological criteria	Environmental criteria	Energy crop
	56%	33%	11%	
1	Excellent	≥Good	≥Neutral	Appropriate
2	Excellent	Excellent	*	Appropriate
3	≤Good	≥Good	Good	Less appropriate
4	≤Good	Excellent	*	Less appropriate
5	Good	*	*	Less appropriate
6	≥Good	Bad	*	Less appropriate
7	≥Good	≤Good	Bad	Less appropriate
8	Bad	Bad	*	Inappropriate
9	Bad	≤Good	≤Neutral	Inappropriate

decision rules that are acquired from the model developer and presented in a tabular form (Table 1).

In our study, we followed these steps to develop the energy crops assessment model, which is presented in detail in the next section.

Simulation Model as Data Source for DEX-i Model

Using technological-economic simulation modeling, one can obtain information about the system itself and its responses to different model input parameters. The relationships between system elements (in this case input material, human labor) are expressed with a series of technological equations that are used for calculation of input usage and outputs produced. For financial and technological analysis of energy crops for biogas production the computer simulation model was developed. There are three basic sub-models:

- the sub model of energy crop production by the farmer (model calculations)
- the sub model of biogas production from energy crops
- the sub model of electricity and heat production from biogas produced from energy crops

The developed model enables calculation of the most important economic parameters such as break-even price, coefficient of profitability, and financial result. Break-even price represents the average total cost per unit of output. There are three break-even prices: BEP farmer (€/kg), BEP el. energy, and BEP heat energy (€/kWh). At BEP farmer, we evaluated the total costs of production for each energy crop and average yield of biomass by farmer. At BEP el. energy and BEP heat energy, we evaluated the total cost of electricity and thermal energy production per kWh for each energy crop in the biogas plant. The prices used in model

Attribute	**Scale**
Energy crop	***Appropriate***; Less appropriate; **Inappropriate**
—**Economic criteria**	**Bad**; Good; ***Excellent***
——Break even price farmer (€/kg)	**High**; Neutral; ***Low***
——Break even price electricity (€/kg)	**High**; Neutral; ***Low***
——Break even price thermal energy (€/kg)	**High**; Neutral; ***Low***
—**Technological criteria**	**Bad**; Good; ***Excellent***
——**Production of biogas**	**Difficult**; Middle difficult; ***Easy***
———The suitability of crops for processing into biogas	***Appropriate***; Less appropriate; **Inappropriate**
———The suitability of crops for manipulation in digestor	***Appropriate***; Less appropriate; **Inappropriate**
———C/N ratio	***Optimal***; **Less optimal**
——**Production of energy crop**	**Difficult**; Middle difficult; ***Easy***
———Difficulty of production	**High**; Medium; ***Low***
———Crop rotation	**Every three years**; Every two years; ***Monoculture***
———**Risks in production**	**High**; Middle; ***Low***
————The risk of hail	**High**; Middle; ***Low***
————Resistance of crops to drought	***Resistant***; Partly resistant; **Non-resistant**
—**Environmental criteria**	**Bad**; Neutral; ***Good***
——Need for fertilizers (nitrogen)	**High**; Medium; ***Low***
——Use of pesticides in production	**High**; Medium; ***Without pesticides***

Fig. 2. Attribute scales.

(prices of input and output parameters) are current prices on the market. Use of pesticides and fertilizers is taken from the sprinkler and fertilization plan, which is part of the sub model of energy crop production by the farmer. Costs of production of energy crops include human labor, which is evaluated in the context of model calculations. Model calculations are prepared each year by the agricultural institute for individual crops. The simulation model output data represent some of the input parameters of analyzed energy crops in multi-criteria decision analysis.

Six energy crops were analyzed:

- Alternative 1: Maize (*Zea mays* L.) sort PR 34N43 (FAO 580)
- Alternative 2: Sorghum (*Sorghum* L.) sort Autan
- Alternative 3: Amaranth (*Amaranthus* sp. L.) sort Acruentus G6
- Alternative 4: Sunflower (*Helianthus annuus* L.) sort PR64A43
- Alternative 5: Jerusalem artichoke (*Helianthus tuberosus* L.)
- Alternative 6: Sugar beet (*Beta vulgaris* sp. L) sort Remos

The Computer Prototype of Simulation Model BIOGAS

The computer prototype of simulation model BIOGAS was developed in order to simplify the work and calculations, and to find alternative solution as soon as possible. The use of appropriate computer programs enables quick and easy calculations.

To develop the model we use the software package MS Excel 2007, combined with the programming language VBA (Visual Basic for Applications). Based on the individual production models, the computer calculates the technological parameters of production, which are the basis for the technological map, with calculations of the total costs. A single model collects data and calculates certain economic parameters (break-even price of production of energy crops, break-even price of production of electricity and heat energy, financial results, the coefficient of economy, etc.) on various input parameters (different inputs, prices, different crops, and biogas yields).

Fig. 3 shows a basic menu of three main sub models of the BIOGAS simulation model.

A computer-based simulation model generates a database of all productions and measurements in the worksheet collection data and collects the estimated parameters for all energy crops from each submodel. The collected data are then passed through a series of programming commands transferred into the table where the economic indicators are calculated for each investment in the processing of energy crops into biogas. Submodel biogas production is based on data obtained by laboratory experiments of anaerobic digestion and is related to other models.

DEXi Model for the Assessment of Energy Crops for Biogas Production

The initial hierarchy of the model was established through the brain-storming of experts involved in model development. The final structure of attributes for the assessment of energy crops is shown in Fig. 4.

In the model, three primary evaluation dimensions were taken into account: economic, technological, and environmental criteria. For each of these, the most relevant attributes were identified. An economic criteria was decomposed into break-even price farmer (€/kg), break-even price electricity (€/kWh) and break-even price thermal energy (€/kWh). Technological criteria consists of attributes that describe the production of biogas (the suitability of crops for processing into biogas and the suitability of crops for manip-

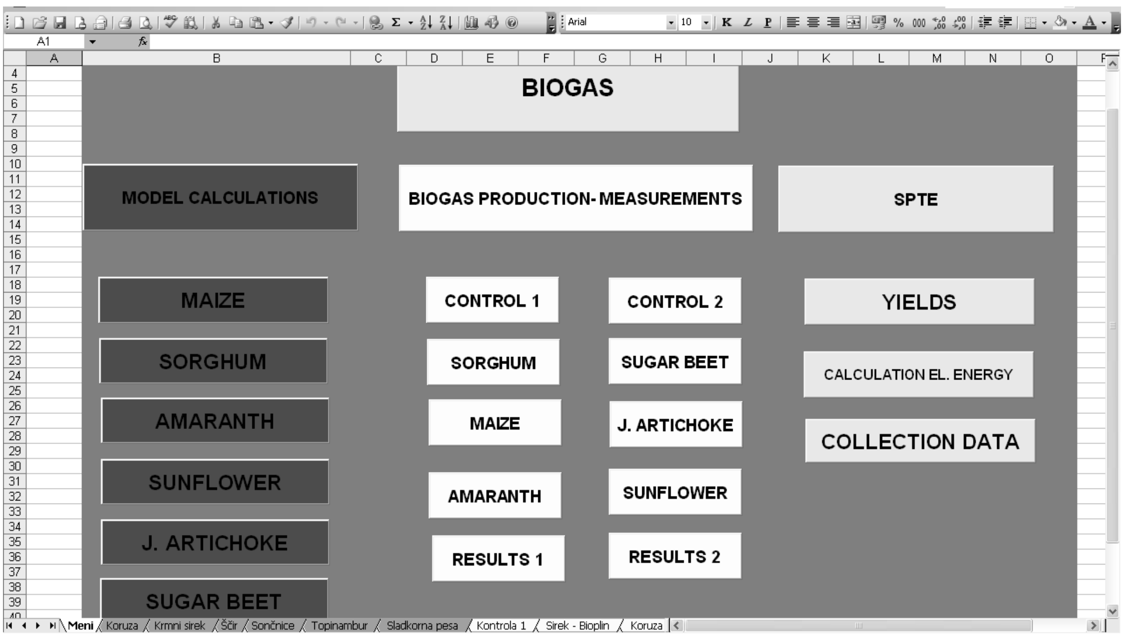

Fig. 3. Basic menu of three main sub models of the BIOGAS simulation model.

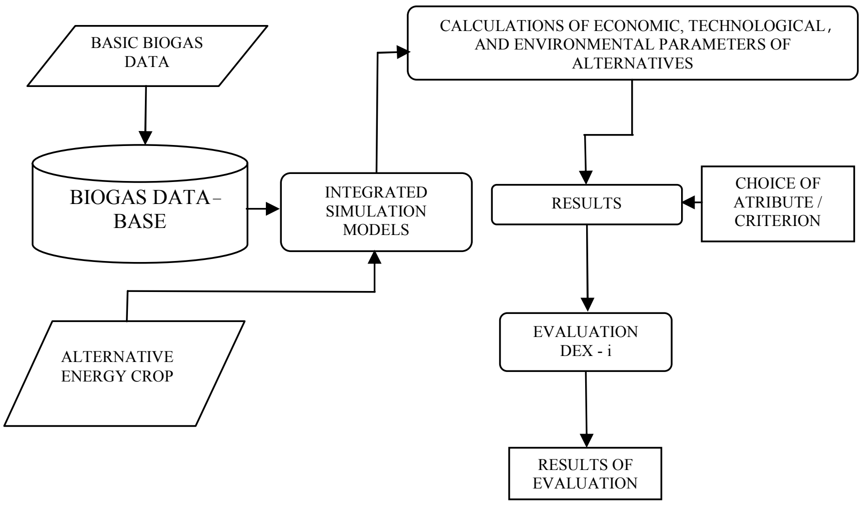

Fig. 4. The structure of the BIOGAS deterministic simulation model.

ulation in digestor and C/N ratio) and production of energy crop (consisting of the difficulty of production, crop rotation, and risks in production (the risk of hail and resistance of crops to drought). Environmental criteria describe the need for fertilizers (nitrogen) and the use of pesticides in production.

Each attribute is assigned to a set of possible qualitative values as described in Fig. 2.

In the last step of DEX-i model development, the decision rules were defined. Decision rules define the aggregation of values in the model from its inputs through intermediate attributes toward the root. Therefore, decision rules have to be defined for all internal attributes, including the root.

Here, in Table 1, we show only one utility function, the one that aggregates the economic, technological, and environmental criteria into the aggregate attribute energy crop.

In Table 1, the decision rules are presented in a so-called complex form where the asterisk ("*") denotes any value and the "≥" stands for "equal to or greater." The relative importance of attributes is also expressed by weights at the top of the table. These weights have been estimated from the rules by DEX-i using a linear regression method [12]. Using the regression, a decision rule is interpreted as a set of points in a multi-dimensional space and approximated with a hyperplane in that space. Let $x_1 \ldots x_n$ represent the input attributes (financial, etc.) and y, the dependent variable, which is required to be ordered. For the purpose of this method, all qualitative values of attributes are represented by their ordinal numbers. Accordingly, we can interpret a decision rule as a collection of points and approximate them by a hyperplane. That means that we find the coefficients a_0, $a_1 \ldots a_n$ so that the approximation is optimal in the least-squares sense [10]. The regression equation is as follows:

$$Y = a_0 + a_1 x_1 + \ldots + a_n x_n \qquad (1)$$

...where:
$a_1 \ldots a_n$ – regression coefficients
$x_1 \ldots x_n$ – ordinal values of attributes

The numerical attributes for the DEX-i analysis were obtained by simulation using the simulation model, while the numerical attributes were estimated based on different data sources. The following qualitative scales were used for numerical sub-attributes (Table 2).

Table 2. 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	
15-30/1	optimum
>30/1	less appropriate
<15/1	less appropriate

Table 3. Qualitative scales for non-numerical attributes.

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

Table 4. The results of biogas production measurements and simulation model for individual energy crops.

	Biogas	Biogas	El. energy	Heat energy	BEP[c] farmer	BEP[c] el. energy	BEP[c] h. energy	C/N ratio
	[Nl/kgVS][a]	[Nm^3/ha][b]	[kWh/ha]	[kWh/ha]	[€/kg]	[€/kWh]	[€/kWh]	
Maize	576	10,332.5	20,665	37,197	0.026	0.18	0.1	01:24
Sorghum	509	7,783.5	15,567	28,020	0.029	0.23	0.13	01:30
Amaranth	421	3,641.4	7,283	13,109	0.782	0.51	0.28	01:14
Sunflower	495	5,749.6	11,499	20,698	0.329	0.28	0.16	01:40
Jerusalem artichoke	463	5,104.8	10,210	18,377	0.079	0.40	0.22	01:42
Sugar beet	649	5,823.3	11,647	20,964	0.038	0.34	0.19	01:33

[a] norm litre per kg of volatile solids (273 K, 1,013 bar),
[b] norm m^3 per hectare,
[c] break-even price

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 3 shows qualitative scales for non-numerical attributes. Finally, attribute values for each alternative are put into the DEX-i evaluation table and analysis is ultimately conducted.

Results and Discussion

By using the BIOGAS technological-economic simulation model, individual alternatives – energy crops were simulated. Using the developed simulation system the technological-economic parameters of production and processing energy crops into biogas were estimated. Six energy crops were analyzed (Fig. 6), described in the section “Simulation Model as Data Source for DEX-i Model.”

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. The results of developed integrated deterministic simulation models depend on quality of incoming data of the model. Table 4 shows the results of the simulation model for the individual alternative.

The simulation results were further evaluated with multi criteria decision model DEX-i. 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 the DEX-i decision model. This is conducted with a classification algorithm based on classification intervals. Fig. 5 shows the results of DEXi evaluation of six energy crops.

The DEX-i evaluation of alternatives (energy crops) with important weights of aggregate attributes is shown in Table 5.

The DEX-i evaluation of alternatives results in the ranking of alternatives: maize, sorghum, sunflower, sugar beet, amaranth, and Jerusalem artichoke (Fig. 6). Using the 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 for exclusion of unacceptable alternatives, but the shortcoming of DEX-i is its inability to separate between alternatives with the same qualitative evaluation.

Conclusion

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

Table 5. DEX-i project evaluation of alternatives with important 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=56%	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=33%	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	non-resistant	partially resistant	resistant	non-resistant	partially resistant	partially resistant
Environment criteria*W=11%	good	good	bad	bad	bad	neutral
Use of fertilizers (nitrogen)	low	low	high	high	high	medium
Use of pesticides	medium	non	medium	high	medium	medium
Ranking	2	3	2	2	3	1

The integrated computer supported simulation model combined with multi-criteria decision analysis presents a suitable methodology tool for a decision support system on farms and biogas plants. The system takes into consideration different independent criteria and enables ranking of alternatives (energy crops for biogas production). The use of 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).

In the presented paper the DEX-i method favored maize, which got the highest DEX-i evaluation. Maize is followed by sorghum, sugar beet, and sunflower, and can be used as an alternative for maize (crop rotation, drought,

Kriterij	Sunflower	Jerusalem artichoke	Sorghum	Sugar beet	Amaranth	Maize
Energy crop	Less appropriate	**Inappropriate**	Less appropriate	Less appropriate	**Inappropriate**	*Appropriate*
├─**Economic criteria**	Good	**Bad**	Good	Good	**Bad**	*Excellent*
│ ├─Break-even price farmer (€/kg)	**High**	Neutral	*Low*	Neutral	**High**	*Low*
│ ├─Break-even price electricity (€/kg)	Neutral	**High**	Neutral	Neutral	**High**	*Low*
│ └─Break-even price thermal energy (€/kg)	Neutral	**High**	Neutral	Neutral	**High**	*Low*
├─**Technological criteria**	**Bad**	**Bad**	Good	**Bad**	**Bad**	Good
│ ├─**Production of biogas**	**Difficult**	**Difficult**	*Easy*	**Difficult**	Middle difficult	*Easy*
│ │ ├─The suitability of crops for processing into biogas	Less appropriate	Less appropriate	*Appropriate*	**Inappropriate**	Less appropriate	*Appropriate*
│ │ ├─The suitability of crops for manipulation in digestor	Less appropriate	**Inappropriate**	*Appropriate*	**Inappropriate**	*Appropriate*	*Appropriate*
│ │ └─C/N ratio	**Less optimal**	**Less optimal**	*Optimal*	**Less optimal**	*Optimal*	*Optimal*
│ └─**Production of energy crop**	**Difficult**	Middle difficult	Middle difficult	**Difficult**	Middle difficult	Middle difficult
│ ├─Difficulty of production	Medium	*Low*	Medium	**High**	*Low*	Medium
│ ├─Crop rotation	**Every three years**	**Every three years**	Every two years	**Every three years**	Every two years	Every two years
│ └─**Risks in production**	**High**	Middle	Middle	Middle	Middle	Middle
│ ├─The risk of hail	**High**	Middle	**High**	*Low*	Middle	**High**
│ └─Resistance of crops to drought	**Non-resistant**	Partly resistant	*Resistant*	**Non-resistant**	Partly resistant	Partly resistant
└─**Environmental criteria**	*Good*	*Good*	**Bad**	**Bad**	**Bad**	Neutral
├─Need for fertilizers (nitrogen)	*Low*	*Low*	**High**	**High**	**High**	Medium
└─Use of pesticides in production	Medium	*Without pesticides*	Medium	**High**	Medium	Medium

Fig. 5. Results of DEXi evaluation of six energy crops, showing all the values of input and aggregate attributes.

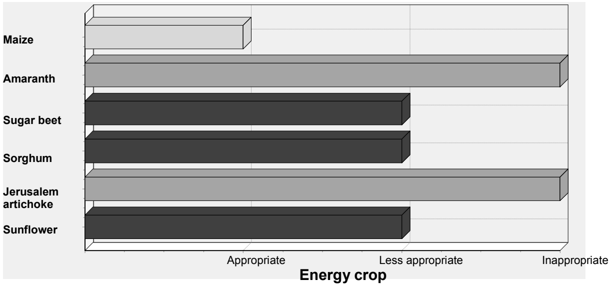

Fig. 6. Graphical representation of the overall energy crop assessment results.

etc.). The next alternatives are amaranth and Jerusalem artichoke, which got the worst evaluation.

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

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