Capturing Uncertainties in Evaluation of Biofuels Feedstocks: A Multi-Criteria Approach for the US

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Abstract

Current research evaluating biofuels policies focuses primarily on market-economic criteria. While it is widely acknowledged that both the economic and environmental, and social aspects of biofuels policy must all be balanced with each other in the process of developing a viable biofuels policy, little progress has been made to date on evaluating these uncertain non-market relationships.

In this paper, we develop a fuzzy theory holistic approach evaluating the 1st, 2nd, and 3rd generation biofuels feedstocks in meeting multiple economic, environmental and social criteria of the biofuels policies and capturing the uncertainties of evaluation processes.

We use a multi-criteria approach PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) and fuzzy set theory to show how missing information, fuzziness, and ambiguity in decision making processes can be considered for a sustainable biofuels policy evaluation.

Key words: biofuels, uncertainties, multi-criteria decision support, PROMETHE, fuzzy set theory, decision making, policy evaluation

Introduction and problem setting

In 2007, the biofuels production in the US amounted to 0.5 million barrels/day and is predicted to increase to 1.7 million barrels/day in 2035 (DOE, 2010). In 2010, the production of ethanol in the US amounted to 12,308.8 million gallons, while the production of biodiesel amounted to 714.6 million gallons (FAPRI, 2011).

The increasing production and consumption of biofuels are triggered by the biofuels policies objectives of: extending the security of the national energy supply, reducing greenhouse gas (GHG) emissions and global warming, creating new market outlets or additional demand for agricultural products, strengthening regional development and finally economic growth. While different objectives have been defined in national biofuels policies of different countries, it should be emphasized that both the achievement of the objectives and the incentives to reach these objectives depend, among others, on economic, environmental, and social conditions, the availability of production feedstocks as well as the biofuels production potential in the respective countries.

Current research evaluating biofuels policies focuses primarily on comparing the costs and benefits of market-economic criteria, such as fuel and biofuels feedstock price relations and price stabilities on national and international markets (Tyner and Taheripour, 2008; Meyer et al., 2009; Banse et al., 2008), biofuels subsidy policies (de Gorter et al., 2009; Wiesenthal et al., 2009), and food security, growth and poverty issues, or welfare economics (Harrison, 2009). In this policy area, however, it is important to consider certain additional environmental and social criteria. According to Runge and Johnson (2008), an evaluation of different biofuels feedstock alternatives and their impacts on, e.g., water quantity and quality, nitrogen loadings, land use changes and GHG emissions is necessary in each country (vs. agro-ecological subzone). Such an evaluation could help national governments and multilateral agencies in determining the most cost-efficient and environment friendly solution in the process of converting biomass to fuel.

In this study, we will address the existing scientific and methodological gap by applying a holistic approach to biofuels feedstocks analysis that augments market-based cost-benefit evaluations with evaluations of environmental and social criteria in one multi-criteria framework, considering at the same time uncertainties resulting for decision makers. We choose to evaluate biofuels feedstocks that are currently used (or are approved to be used in the future) in the US, which has the highest ethanol production in the world and simultaneously, it is the third biggest biodiesel producer.

The paper is structured as follows. The next chapter defines the research objectives. Further, the methodology and data are presented followed by a theoretical chapter on fuzzy set theory and the results. Finally, conclusions are presented.

Research objectives

The main goal of this paper is to analyze the 1st, 2nd, and 3rd generation biofuels feedstocks in the US and their performance in meeting multiple tangible and intangible economic, environmental and social criteria of biofuels policies. The evaluation of different biofuels feedstocks and policies is often plagued by uncertainties that can result from the complexity of the policy goals and constraints, imprecision of the policy objectives, or incomplete or vague information about policy options. In this paper, we approach this question by applying fuzzy set theory and introduce a fuzzy multi-criteria evaluation approach F-PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations).

As this kind of holistic multi-criteria approach has not been used to date for analyzing biofuels policies, the presented analysis is a useful step of a non-market valuation in the biofuels research.

Methodology and data

To investigate the performance of biofuels feedstocks for biofuels production in terms of economic, environmental and social criteria in uncertain environment, we develop a methodological framework combining the following approaches:

1 Expert elicitation,
2 Fuzzy set theory, and
3 F-PROMETHEE.

We include the following feedstocks for ethanol and biodiesel production: corn (a_1), soybean (a_3), canola/rapeseed (a_4) (1st generation biofuels feedstocks), switchgrass (a_2) (2nd generation biofuels feedstock) and algae (a_5) (3rd generation biofuels feedstock). We chose these feedstocks, as they are the most important feedstocks currently used (corn, soybean and canola) or in experimental production stage (switchgrass and algae) to be used in the future for biofuels production in the US. Based on statistical data, we define canola to be equivalent to rapeseed in terms of the analyzed variables. Moreover, we do not consider the technology costs in the production process of the respective feedstocks, but rather focus on the direct feedstock production costs.

We use data from FAPRI data base as well as from various experimental publications (Mata et al., 2010; Dinh et al., 2009; Pimentel and Patzek, 2005).

Expert elicitation

As environmental and social objectives of biofuels policies are mostly intangible and/or difficult to measure, currently available data and information is insufficient to evaluate, using standard econometric techniques, either the relative importance of economic, environmental, and social objectives or the relationships between alternative policy options and these objectives. Accordingly, we approach this problem by eliciting opinions from six experts in the field of biofuels policies about how objectives should be weighted, and about how policies relate to these objectives. With the expert elicitation approach, we seek to elicit a credible account of probabilistic information regarding uncertainty in the evaluation of biofuels feedstocks. We also show that expert estimations are a necessary element of policy evaluation that allow considering both tangible and intangible policy criteria in decision making processes.

The experts have been asked to assess the importance of the defined biofuels policy objectives and the performance of the analyzed biofuels feedstocks in terms of these objectives, such as: 'Reducing biofuels production costs', 'Increasing biofuels productivity/acre', 'Insuring national food security', 'Securing farmers' incomes', 'Reducing greenhouse gas emissions', 'Reducing water usage', 'Reducing land use', 'Protecting biodiversity and landscapes', 'Increasing consumer welfare', 'Supporting rural communities', 'Improving health and safety issues', Creating new jobs'.

The experts estimated the relative importance of the objectives using the numeric scale 1-10, with the following scale estimates: 1-3 – low importance, 4-6 – middle importance, 7-10 – high importance. For the estimation of the biofuels feedstocks in terms of the enumerated objectives, the linguistic scale (a basic tool of fuzzy set theory) was applied (table 1) and further translated into triangular fuzzy numbers.

Table 1 Linguistic variables and triangular fuzzy numbers

Linguistic variable	**Triangular fuzzy number**
Very low (VL)	(0.00, 0.00, 0.25)
Low (L)	(0.00, 0.25, 0.50)
Medium (M)	(0.25, 0.50, 0.75)
High (H)	(0.50, 0.75, 1.00)
Very high (VH)	(0.75, 1.00, 1.00)

Source: Authors' performance

Fuzzy set theory – theoretical background

Fuzzy logic allows us to model epistemic (systematic) uncertainty associated with the lack of/or limited knowledge about the policy objectives (criteria), instruments (alternatives) and the outcomes of their implementation.

The analysis is based on the concept of the membership function representing the numerical 'degree of membership' ($\mu_{\tilde{A}}(x)$) of each element x in a fuzzy set Ã and in the universe X on the real continuous interval between 0 (non membership) and 1 (complete membership). Since the universe X can accommodate full membership, partial membership or non-membership, the fuzzy set theory allows treating fuzziness in a quantitative way. We follow the approach of De Luca and Termini (1972), according to which the following criteria for measuring fuzziness *fuz*(A) of the set A, need to be satisfied:

1 $fuz(A) = 0,\ iff\ \mu_A(x) = 0\ or\ \mu_A(x) = 1,\ \forall x \in A$

2 $fuz(A) = maximum, \; iff \; \mu_A(x) = 1/2, \; \forall x \in A$

3 $fuz(A) \leq fuz(B), \; iff \; \forall x \in A, \; either \; \mu_A(x) \leq \mu_B(x) \; whenever \; \mu_B(x) < \frac{1}{2}$,
$or \; \mu_A(x) \geq \mu_B(x) \; whenever \; \mu_B(x) > \frac{1}{2}$, and

4 $fuz(A) = fuz(\sim A)$

We define a fuzzy number (fuzzy interval) as a fuzzy set defined on the real interval which has a quantitative meaning. A fuzzy set that is a fuzzy number is characterized by the following properties:

- It is normal ($[sup_{x \in X} \mu(x) = 1]$).
- The α-cuts are closed intervals for all values of $\alpha \in (0,1]$, s.t. (${}^{\alpha}\mu = \{x \in X: \mu(x) \geq \alpha\}$, and ${}^{\alpha+}\mu = \{x \in X: \mu(x) > \alpha\}$, where $\alpha \in [0, 1]$, and α - threshold value (confidence level).
- Its support is bounded.[1]

We apply the triangular L-R fuzzy number $(m, \alpha, \beta)_{LR}$ represented with the following membership function:

$$\mu(x) = \begin{cases} \mu_L(x) = L\left[\dfrac{(m-x)}{\alpha}\right], & for\; x < m, \alpha \in R^+ \\ 1, & for\;\; x = m \\ \mu_R(x) = R\left[\dfrac{(x-m)}{\beta}\right], & for\;\; x \geq m, \beta \in R^+ \end{cases}$$

where *m, α, β* are the middle value, the lower and upper bounds of the support of the fuzzy number, respectively, while $\mu_L(x)$ is a monotonically increasing membership function and $\mu_R(x)$ is a monotonically decreasing function (not necessarily symmetrical to $\mu_L(x)$). In addition, the functions *L* and *R* possess the following properties:

1 $L(u) \in [0, 1] \; \forall \; u \; and \; R(u) \in [0, 1] \; \forall \; u$

2 $L(0) = R(0) = 1$

3 $L(u) \; and \; R(u) \; are \; decreasing \; in \; [0, \infty]$

4 $L(1) = 0 \; if \; \min_u L(u) = 0$

$\lim_{u \to \infty} L(u) = 0 \; if \; L(u) > 0, \forall \; u$ and

$\mathrm{R}(1) = 0 \; if \; \min_u R(u) = 0$

$\lim_{u \to \infty} R(u) = 0 \; if \; R(u) > 0, \forall \; u.$

Assuming that A and B are two fuzzy subsets of the universe of the discourse X, and describe the membership functions $\mu_{\tilde{A}}(x_i), \; \mu_{\tilde{B}}(x_i)$, respectively, the following operations were applied:

1 Union (OR) $\forall \; x_i \in X, \mu_{\tilde{A} \cup \tilde{B}}(x_i) = \max \; [\mu_{\tilde{A}}(x_i), \mu_{\tilde{B}}(x_i)] = \; \mu_{\tilde{A}}(x_i) \vee \mu_{\tilde{B}}(x_i)$

2 Intersection (AND) $\forall \; x_i \in X, \mu_{\tilde{A} \cap \tilde{B}}(x_i) = \min \; [\mu_{\tilde{A}}(x_i), \mu_{\tilde{B}}(x_i)] = \; \mu_{\tilde{A}}(x_i) \wedge \mu_{\tilde{B}}(x_i)$

3 Complement $\forall \; \mathrm{x_i} \in \mathrm{X}, \mu_{\tilde{\mathrm{A}}}(\mathrm{x_i}) = 1 - \mu_{\tilde{\mathrm{A}}}(\mathrm{x_i})$

4 Inclusion $\forall \; x_i \in X, \mu_{\tilde{A} \supset \tilde{B}}(x_i), \; iff \;\; \mu_{\tilde{A}}(x_i) \geq \; \mu_{\tilde{B}}(x_i)$

[1] Detailed information on the characteristics of a fuzzy number and fuzzy sets can be found, e.g., in Hersh (2006).

Fuzzy multi-criteria PROMETHEE approach for biofuels feedstocks

To evaluate biofuels feedstocks in terms of multiple criteria, we develop a fuzzy approach F-PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations) which was initially introduced as a crisp model by Brans (1982) and Brans et al. (1984).

In a fuzzy decision environment, we consider that each objective (criterion) from the finite set C_j, such as $C_j = \{c_1, c_2, \dots, c_m\}$, can be expressed as a fuzzy subset over the finite set of decision alternatives (feedstocks) $A_i = \{a_1, a_2, \dots, a_n\}$. Hence, the grade of membership of the alternative a_i in C_j ($\mu_{C_j}(a_i)$) indicates the degree to which a_i satisfies the objective c_m. We use the Bellman and Zadeh's (1970) max-min operator, according to which the decision function *D* can be expressed as follows:

$$\forall\, a_i \in A, \qquad D(a_i) = \mathrm{MIN_j}\ \mu_{C_j}(a_i), \qquad s.t. (j = 1, 2, \dots, m)$$

As we look for a maximum value over the alternatives in *D* to find the 'best' solution $B*$ that maximizes the decision function *D* and satisfies the condition, the decision function has the form:

$$D(B^*) = \mathrm{MAX_i}\left\{\mathrm{MIN_j}\left[\mu_{C_j}(a_i)\right]\right\},\ \forall\, a_i \in A\ \ s.t.\ \ (i = 1, 2, \dots, n).$$

The multi-criteria problem is expressed as a decision matrix ($m\times n$), while the matrix elements indicate the evaluation of the alternative a_i in terms of the criterion c_j to be optimized.

The criteria weights were considered as crisp numbers as the preferences of alternative solutions are fuzzy (as they can be determined only approximately) while the preferences of the decision makers in terms of the importance of the respective objectives are not (and can therefore be described with precise numerical values) (compare: Goumas and Lygerou, 2000). A weight vector for all objectives $w_j = \{w_1, w_2, \dots, w_{12}\}$ was defined as:

$$w_j = \frac{1}{n}\left[\sum_{e=1}^{n} w_j^e\right]$$

It reflects the relative importance of each criterion in the frame of all criteria, where:
w_j – priority weight of the criterion j, $\forall\, j, w_j \in R, and\ j = (1, 2, \dots, 12)$
n – number of experts, with $n = 6,\ and\ n = \{e\},\ s.t. e = (1, 2, \dots, 6)$.

The fuzzy ratings of each alternative ($A_i,\ \forall\, i = 1, 2, \dots, n$) in terms of each criterion ($C_j,\ \forall\, j = 1, 2, \dots, m$) in the fuzzy decision matrix $\widetilde{D} = [\tilde{x}_{ij}]_{m\times n}$ were expressed as triangular fuzzy numbers $\tilde{x}_{ij} = (x_{ia}, x_{ib}, x_{ic}), \forall\, i, j, x_{ij} \in R$ and calculated as follows:

$$\tilde{x}_{ij} = \frac{1}{n}\left[\sum_{e=1}^{n} \tilde{y}_{ij}^e\right] = \frac{1}{n} \odot \left[\tilde{x}_{ij}^e \oplus\ \tilde{x}_{ij}^e \oplus\ \dots \oplus \tilde{x}_{ij}^e\right] = \left(\frac{1}{n}\sum_{n=1}^{n} x_{ia}, \frac{1}{n}\sum_{n=1}^{n} x_{ib}, \frac{1}{n}\sum_{n=1}^{n} x_{ic}\right)$$

$\tilde{x}_{ij}^e$ – fuzzy rating of the alternative i (a_i) with respect to the criterion j (c_j), $\forall\, i = 1, 2, \dots, n\ and\ \forall\, j = 1, 2, \dots, m$) for the eth expert
$\odot$ - fuzzy multiplication operator,
$\oplus$ - fuzzy addition operator.

The preferences between the biofuels feedstocks alternatives were conducted by using the concept of the fuzzy difference $\widetilde{d}_j(\tilde{x}_{aj}, \tilde{x}_{bj}) = c_j(\tilde{x}_{aj}) - c_j(\tilde{x}_{bj})$, such that:

$$\widetilde{d_j}(\tilde{x}_{aj}, \tilde{x}_{bj}) = [d_j(\tilde{x}_{aj,} \tilde{x}_{bj})^{\alpha}, d_j(\tilde{x}_{aj,} \tilde{x}_{bj})^{m}, d_j(\tilde{x}_{aj,} \tilde{x}_{bj})^{\beta}]$$

$$\Rightarrow \begin{cases} \tilde{x}_{aj}{}^{\alpha} - \tilde{x}_{bj}{}^{\beta},\ \tilde{x}_{aj}{}^{m} - \tilde{x}_{bj}{}^{m},\ \tilde{x}_{aj}{}^{\beta} - \tilde{x}_{bj}{}^{\alpha}, & iff\ \tilde{x}_{aj} \not\equiv \tilde{x}_{bj} \\ (0,0,0), & iff\ \tilde{x}_{aj} = \tilde{x}_{bj} \end{cases}$$

Based on the fuzzy difference, the fuzzy preference function $\tilde{P}_j(a,b)$ was derived measuring the intensity of the total preference for an alternative a compared to an alternative b in the alternative set A. Therefore:

$\tilde{P}_j(a,b) = \tilde{P}_j(\tilde{d}_j) = F_j[\widetilde{d_j}(\tilde{x}_{aj},\ \tilde{x}_{bj})],\ \forall\ \tilde{x}_{aj},\ \tilde{x}_{bj},\ a,\ b \in A_j$ and

$$F_j[\widetilde{d_j}(\tilde{x}_{aj}, \tilde{x}_{bj})] = P_j(\alpha, m, \beta)_{LR} = (P_j(m) - P_j(m-\alpha);\ P_j(m);\ P_j(m+\beta) - P_j(m)).$$

For this study, we chose the V-shape preference function with the following condition:

$$P_j(\tilde{d}) = \begin{cases} 0, & m - \alpha \le 0 \ \rightarrow\ indifference\ between\ \tilde{x}_{aj}\ and\ \tilde{x}_{bj} \\ \dfrac{(\alpha, m, \beta)}{p}, & 0 \le m - \alpha\ and\ m + \beta \le p \rightarrow increasing\ preference\ of\ \tilde{x}_{aj}\ over\ \tilde{x}_{bj} \\ 1, & m + \beta > p \ \rightarrow\ strict\ preference\ of \tilde{x}_{aj}\ over\ \tilde{x}_{bj} \end{cases}$$

The decision parameter *p* was considered as a crisp number in order to avoid the risks of fuzzy multiplication, which could lead to excessive fuzziness (Ribeiro, 1996) or inevitable approximation (Dubois and Prade, 1979; Hanss, 2005). The preference level *p* was estimated based on the relative importance of each criterion in terms of all defined criteria.

If a criterion is to be maximized, the preference function shows the preference of *a* over *b* for the observed deviations between the alternative evaluations on the criterion c_j. If the deviations are negative, the preference is equal to zero. If a criterion is to be minimized, the preference function is reversed: $\tilde{P}_j(a,b) = F_j[-\widetilde{d_j}(\tilde{x}_{aj},\ \tilde{x}_{bj})]$. Since $\tilde{P}_j(a,b)$ is strictly positive if $\widetilde{d_j}(\tilde{x}_{aj},\ \tilde{x}_{bj})$ is negative, the positive opposite difference was also calculated: $\widetilde{d_j}(\tilde{x}_{aj},\ \tilde{x}_{bj}) = -\widetilde{d_j}(\tilde{x}_{aj},\ \tilde{x}_{bj})$. Therefore, both $\tilde{P}_j(a,b)$ and $\tilde{P}_j(b,a)$ were estimated, such that:

$$\tilde{P}_j(\tilde{d}_j) = \begin{cases} \tilde{P}_j(a,b), & iff\ \tilde{d}_j > 0 \\ \tilde{P}_j(b,a), & iff\ \tilde{d}_j < 0 \end{cases}$$

In a next step, the aggregated multi-criteria preference indices $\widetilde{\Pi}(a,b)$ and $\widetilde{\Pi}(b,a)$ were calculated, according to the formula:

$$\widetilde{\Pi}(a,b) = \frac{\sum_{j=1}^{c_j}[w_j \otimes \tilde{P}_j(a,b)]}{\sum_{j=1}^{c_j} w_j} = \frac{\sum_{j=1}^{c_j}[(w_j{}^{\alpha}, w_j{}^{m}, w_j{}^{\beta}) \otimes (P_j{}^{\alpha}, P_j{}^{m}, P_j{}^{\beta})]}{\sum_{j=1}^{c_j}(w_j{}^{\alpha}, w_j{}^{m}, w_j{}^{\beta})}$$

with w_j expressing the relative importance of the criterion *j*.

Based on the aggregated multi-criteria preference index, fuzzy outranking flows for each alternative a_i were estimated.

The positive flow (*outgoing/leaving flow*) $\tilde{\phi}^{+}(a,b)$ is measuring the strength of all alternatives $a_i \in A$, while the negative flow (*incoming/entering flow*) $\tilde{\phi}^{-}(a,b)$ is measuring the weakness of all alternatives $a_i \in A$:

$$\tilde{\phi}^{+}(a,b) = \sum_{i=1}^{i} \widetilde{\Pi}(a,b),\ for\ \forall\ a_i \in A, \qquad \tilde{\phi}^{-}(a,b) = \sum_{i=1}^{i} \widetilde{\Pi}(b,a),\ for\ \forall\ a_i \in A$$

For all alternatives a_i it applies:

$\tilde{\phi}^{+}(a,b) = (\tilde{\phi}^{+}{}_{\alpha}(a),\ \tilde{\phi}^{+}{}_{m}(a),\ \tilde{\phi}^{+}{}_{\beta}(a))$, *where*

$\tilde{\phi}^{+}{}_{\alpha}(a) = \sum_{i=1}^{i} \tilde{\Pi}_{\alpha}(a,b),\ \tilde{\phi}^{+}{}_{m}(a) = \sum_{i=1}^{i} \tilde{\Pi}_{m}(a,b),\ \tilde{\phi}^{+}{}_{\beta}(a) = \sum_{i=1}^{i} \tilde{\Pi}_{\beta}(a,b)$

and

$\tilde{\phi}^{-}(a,b) = (\tilde{\phi}^{-}{}_{\alpha}(a),\ \tilde{\phi}^{-}{}_{m}(a),\ \tilde{\phi}^{-}{}_{\beta}(a))$, *where*

$\tilde{\phi}^{-}{}_{\alpha}(a) = \sum_{i=1}^{i} \tilde{\Pi}_{\alpha}(b,a),\ \tilde{\phi}^{-}{}_{m}(a) = \sum_{i=1}^{i} \tilde{\Pi}_{m}(b,a),\ \tilde{\phi}^{-}{}_{\beta}(a) = \sum_{i=1}^{i} \tilde{\Pi}_{\beta}(b,a).$

In order to rank the fuzzy flows and to defuzzify the fuzzy numbers, we use the Yager index that is determined by the center of weight of the surface representing its membership function (Yager, 1981):

$$F(\phi) = \int_{0}^{\alpha_{max}} \phi_{\alpha}^{\vee} d\alpha$$

where $\phi_{\alpha}^{\vee}$ is the center (mean value) of the interval ϕ_{α} and α_{max} is the maximum value of $\phi's$ membership grade ($\alpha_{max} = 1$).

The defuzzified $\phi^{+}(a)\ and\ \phi^{-}(a)$ values were further used for estimating the partial and complete ranking of the alternatives (PROMETHEE I and PROMETHEE II).

The PROMETHEE I partial ranking is expressed with preference (P^{I}), indifference (I^{I}), and incomparability (R^{I}) estimated according to the following properties:

$$aP^{I}b, \quad iff \begin{cases} \phi^{+}(a) > \phi^{+}(b)\ and\ \phi^{-}(a) < \phi^{-}(b), or \\ \phi^{+}(a) = \phi^{+}(b)\ and\ \phi^{-}(a) < \phi^{-}(b), or \\ \phi^{+}(a) > \phi^{+}(b)\ and\ \phi^{-}(a) = \phi^{-}(b) \end{cases}$$

$$aI^{I}b, \quad iff \quad \phi^{+}(a) = \phi^{+}(b)\ and\ \phi^{-}(a) = \phi^{-}(b)$$

$$aR^{I}b, \quad iff \begin{cases} \phi^{+}(a) > \phi^{+}(b)\ and\ \phi^{-}(a) > \phi^{-}(b), or \\ \phi^{+}(a) < \phi^{+}(b)\ and\ \phi^{-}(a) < \phi^{-}(b) \end{cases}$$

PROMETHEE II approach is expressed with preference (P^{II}) and indifference (I^{II}), and provides a complete ranking of all alternatives with the *net outranking flow*:

$\phi^{net}(a) = \phi^{+}(a) - \phi^{-}(a)$, such that:

$$\begin{cases} aP^{II}b \quad iff \quad \phi^{net}(a) > \phi^{net}(b), \\ aI^{II}b \quad iff \quad \phi^{net}(a) = \phi^{net}(b) \end{cases}$$

When implementing PROMETHEE II, all alternatives are comparable, and no incomparability remains. Additionally, the following applies:

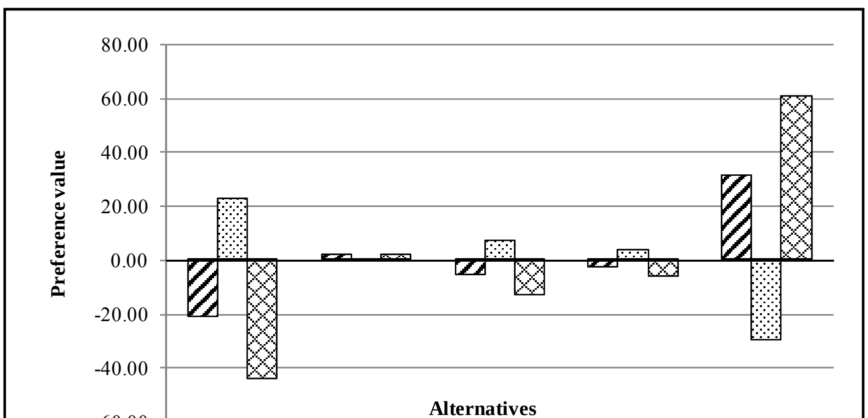
$$\begin{cases} -1 \leq \phi^{net}(a) \leq 1, \\ \sum_{a \in A} \phi^{net}(a) = 0 \end{cases}$$

When $\phi^{net}(a) > 0$, the alternative a is outranking all other alternatives on all criteria, while when $\phi^{net}(a) < 0$, the alternative a is outranked.

Multi-criteria evaluation of biofuels feedstocks in uncertain environment – results and discussion

In the base-case scenario (with the objectives weights estimated by experts), algae for biodiesel have the highest preference values and are thus most promising in satisfying the analyzed economic, environmental and social criteria cumulatively, followed by switchgrass for ethanol, canola/rapeseed and soybean for biodiesel, and corn for ethanol production (figure 1).

Figure 1 ϕ^{+}, ϕ^{-} and ϕ^{net}values and PROMETHE II ranking of the biofuels feedstocks in base-case scenario



	Corn	Switchgrass	Soybean	Canola	Algae
PI +	-21.26	1.72	-5.73	-2.35	31.20
PI -	22.53	-0.30	7.20	3.79	-29.64
PI Net	-43.79	2.03	-12.94	-6.14	60.84

Source: Authors' calculations

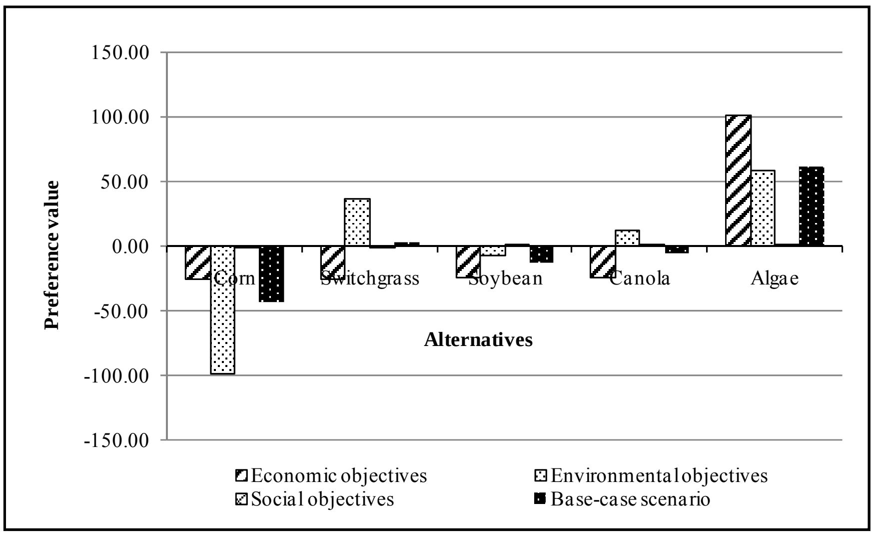
In the reality of policy-making, different objectives have different priorities. To visualize the impact of changing objective priorities on the final implementation of the policy instruments we investigate the ranking of the alternatives in the situation of considering the economic, environmental, and social criteria separately and assuming the maximum relevance of the respective criterion (100%) (Figure 2).

It can be clearly stated that algae (a_5) has the highest importance among all alternatives and is ranked at the first place with the highest ϕ^{net} value, both when maximizing the economic and the environmental objectives. This does not apply to social criteria, when algae takes only the third place in the ranking of the alternatives. In the scenario of considering the economic objectives only, the alternatives can be ranked in the following order, according to their performance: algae → canola → soybean → corn → switchgrass ($a_5 \rightarrow a_4 \rightarrow a_3 \rightarrow a_1 \rightarrow a_2$).

While algae are outranking the other feedstocks, the preference values for the remaining alternatives are very similar. This means that corn, switchgrass, soybean and canola are indifferent in terms of maximizing the economic benefits (such as: 'Reducing biofuels production costs', 'Increasing biofuels productivity/acre', 'Insuring national food security', 'Securing farmers' incomes'). In addition, a very similar pattern in the ranking of the alternatives was found for the economic and social criteria with the following ranking of the alternatives: soybean → canola → algae → corn → switchgrass ($a_3 \rightarrow a_4 \rightarrow a_5 \rightarrow a_1 \rightarrow a_2$). In both scenarios, switchgrass and corn have the worst performance.

When considering solely the environmental objectives, algae and switchgrass are the optimal alternatives in terms of maximizing the environmental objectives (such as: 'Reducing greenhouse gas emissions', 'Reducing water usage', 'Reducing land use', 'Protecting biodiversity and landscapes'), while corn and soybean have the worst performance.

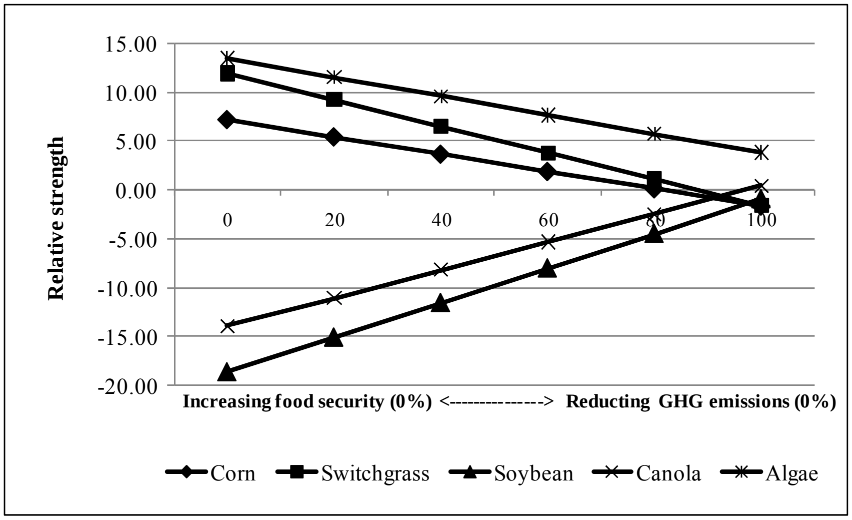
Figure 2 Ranking of biofuels alternatives in different scenarios of considering the economic, environmental, and social policy objectives separately and compared to base-case scenario



Source: Author's calculation

In political programs, some policy objectives may be defined as more or less important. Here, we analyze the question of changing the importance of the objectives and the resulting changes in the ranking of the alternatives. For this purpose, we present an example of tradeoffs between the feedstocks in terms of changing importance of two key objectives of the biofuels policy: the economic objective 'Insuring national food security' and the environmental objective 'Reducing greenhouse gas emissions'. We parameterize the objective 'Insuring national food security' by changing its weights between 0 and 1 (i.e. 0-100%) while simultaneously changing the weights of the objective 'Reducing greenhouse gas emissions' in the opposite direction. The analysis shows that weighting objectives can considerably influence the performance of the alternatives in maximizing those objectives, and consequently the ranking of the alternatives (figure 3).

Figure 3 Tradeoffs between feedstocks in terms of the objectives ‘Insuring national food security’ and ‘Reducing greenhouse gas emissions’



Source: Author’s calculation

When parameterizing the objective ‘Insuring national food security’ between 0 and 1, the net preference values of the alternatives a_5, a_2 and a_1 are decreasing while the net preference values of the alternatives a_3 and a_4 are increasing. This means that with an increasing importance of the objective ‘Insuring national food security’ (and simultaneously with a decreasing importance of the objective ‘Reducing greenhouse gas emissions’), the alternatives a_5, a_2 and a_1 (algae, switchgrass, corn) are performing worse when maximizing national food security, while the alternatives a_3 and a_4 (soybean, canola) can contribute to a higher extent to achieving this objective. Thus, finally the ranking of the alternatives is changing.

When maximizing the objective ‘Insuring national food security’ (importance level = 100%), the alternatives a_5 and a_4 have the highest performance with their respective ϕ^{net} values equal to 3.81 and 0.41. Moreover, the alternatives a_2 and a_3 have the same net flow values, which means that in this scenario both alternatives can contribute to the achievement of the objective ‘Insuring national food security’ to the same extent. The ranking of the alternatives maximizing the objective is as follows: $a_5 \rightarrow a_4 \rightarrow a_2 = a_3 \rightarrow a_1$ (algae → canola → switchgrass = soybean → corn). By contrast, if the objective ‘Reducing greenhouse gas emissions’ has the highest importance level (weight = 100%), the alternatives should be implemented in the following order: $a_5 \rightarrow a_2 \rightarrow a_1 \rightarrow a_4 \rightarrow a_3$ (algae → switchgrass → corn → canola → soybean) in order to maximize the objective achievement.

Conclusions

In this paper, we have shown how missing information, fuzziness, and ambiguity in decision making processes can be included in the evaluation and design process of a sustainable biofuels policy.

The analysis shows that in the base-case scenario including all economic, environmental and social objectives (as defined), algae and switchgrass are most promising in reaching those objectives.

The scenario of changing objective priorities visualizes the impact of each objective on the performance of the biofuels feedstocks. When maximizing economic and environmental objectives, algae are the optimal alternatives while the performance of the other alternatives is varying. Therefore, when evaluating policy instruments, the priorities of the policy objectives should be specified by stakeholders in a deterministic way.

The presented analysis also shows the tradeoffs between the biofuels feedstocks in terms of the objectives ‘Insuring national food security’ and ‘Reducing greenhouse gas emissions’. In the scenario of maximizing the objective ‘Insuring national food security’, the performance of the alternatives has the following ranking: algae → canola → switchgrass = soybean → corn, while switchgrass and corn are indifferent in terms of maximizing this objective. In the scenario of maximizing the objective ‘Reducing greenhouse gas emissions’, the following ranking allows reaching the optimum: algae → switchgrass → corn → canola → soybean.

In evaluation processes, policy objectives should be clearly specified. Including additionally objective weights as fuzzy numbers would allow considering uncertainties related to weight assessments. However, it would simultaneously hinder sensitivity analyses.

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