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Fuzzy Multi-Criteria Framework for Supporting Biofuels Policy Making

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***Abstract*—**In this paper, a fuzzy algorithm and a fuzzy multi-criteria decision framework are developed and used for a practical question of optimizing biofuels policy making. The methodological framework shows how to incorporate fuzzy set theory in a decision process of finding a sustainable biofuels policy among several policy options. Fuzzy set theory is used here as a tool to deal with uncertainties of decision environment, vagueness and ambiguities of policy objectives, subjectivities of human assessments and imprecise and incomplete information about the evaluated policy instruments.

***Keywords*—**Fuzzy set theory, multi-criteria decision-making support, uncertainties, policy making, biofuels

I. Introduction and Research Objectives

In recent years, many investigations have been conducted on biofuels policies (both biodiesel and ethanol production) and their implications on different sectors. Most of these studies address such questions as: price stability on national and international markets [1]-[3], subsidy policies [4], [5], welfare economics, growth and poverty, and food security [6]. While most research is focused on market and price implications, little research has been done on environmental or social effects of biofuels [7-11]. Also, there is no common framework addressing multiple economic, environmental and social policy criteria simultaneously (compare: Ziolkowska and Simon, 2010).

In addition, most studies analyzing biofuels policies are based on crisp models with precisely defined and exact data. As most decisions are taken in uncertain environment of available resources, limited information about policy instruments, or complex decision goals and constraints, the standard crisp models and econometric techniques are not capable of addressing uncertainties of decision-making processes.

In order to address the enumerated uncertainty questions and to analyze a sustainable biofuels policy, a framework is necessary that allows to construct a policy solution that will be cost-effective, environmentally friendly and socially acceptable. To fill this gap, we propose a holistic approach and a fuzzy decision-making framework to biofuels policy analysis that incorporates both market-based cost-benefit evaluations and environmental and social criteria.

As fuzzy set theory has not been implemented in the field of multi-criteria evaluations for biofuels policies to date, the presented research suggests a new approach both from the scientific and policy-making perspective.

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For the analysis, five biofuels policy instruments were chosen: 'Tax credit', 'Mandatory blending', 'Import tariff barriers', 'Rural development/ Renewable energy programs', and 'Biofuels quality certification systems' that are currently implemented in the US and the European Union (EU). The analysis is based on a survey with ten US experts specializing in the field of the biofuels policy.

II. Biofuels Policy Instruments

A number of different policy instruments has been implemented to date in the US and the EU to support and boost the biofuels production and consumption.

Biofuels tax credit is one of the most effective instruments to support the biofuels prices and create an incentive for producers. In the US, the current ethanol tax credit amounts to $0.45/gal and to $1.00/gal for biodiesel, while $1.01/gal for cellulosic ethanol. In the EU, fuel excise tax relief is the most important instrument in providing subsidies for biofuels. In 2006, the tax credit amounted to €0.74/liter ethanol and €0.50/liter for biodiesel.

Another instrument is mandatory blending (mandates) that is expected to increase the consumer price of biofuels and therefore transport fuel, however it can be offset with governmental subsidies (e.g, excise tax exemptions), where some of the costs of the measure are passed on to taxpayers. In the US, the mandate amounts to 6.5 billion gallons in 2010 and is supposed to reach the level of 16 billion gallons by 2022. In the EU policy, the mandatory targets were established voluntarily by some EU countries (Germany, Belgium, Luxembourg, Denmark, Spain, France, Italy, Netherlands, UK, Austria, Finland, Czech Republic, Estonia, Latvia, Lithuania, Slovakia, Romania, Bulgaria) in addition to indicative targets and are not an obligation from the EU [12].

Tariff barriers for biofuels have been introduced with the aim of protecting national biofuels markets from the cheaper imports from the third countries, e.g. Brazil. In the US, the import tariffs have been set at the level of $0.54/gal while in the EU the average import tariff amounts to €0.15/liter [13].

The bioenergy production can be also supported by numerous rural development or renewable energy programs. In the EU, an energy crop premium of €45/ha on a maximum of 2.0 million ha of set aside land was provided by the Common Agricultural Policy (CAP), which however was further abolished by the 'Health Check' reform of 2007. Currently, other measures in the second pillar of CAP can be used to support bioenergy production and consumption. As of August 2011, none of such measures have been officially adopted in the US biofuels policy. A new instrument supporting the biofuels production and consumption is the

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biofuels quality certification system. The purpose of this instrument is to restrict imported raw materials and biofuels by subjecting them to stricter GHG reduction requirements. Furthermore, limits for biofuels from sensitive areas, forests, and partly drained peat lands will be established within this measure in order to promote sustainable solutions in biofuels policies. The quality certification system is still outstanding to be developed and implemented as a legal rule. Thus, this measure can be seen as a future-oriented policy instrument.

By using fuzzy set theory and multi-criteria decision making approach PROMETHEE (Preference Ranking Organization Method for Enrichment Evaluations), in this study we analyze which of the presented policy instruments is most sustainable in meeting multiple economic, environmental and social criteria of the biofuels policy.

III. Methodology and Data

The presented methodological framework consists of the following approaches: expert elicitation, fuzzy set theory, and fuzzy PROMETHEE approach.

In this analysis, the following policy instruments were included: Tax credit (a_1), Mandatory blending (a_2), Import tariff barriers (a_3), Rural development/Renewable energy programs (a_4), and Biofuels quality certification systems (a_5).

The biofuels policies have been evaluated in terms of the following criteria (objectives):

a) Economic criteria: Insuring national food security, Increasing national energy independence, Securing farmers' incomes, Increasing economic growth and development,

b) Environmental criteria: Reducing greenhouse gas emissions, Supporting renewable energy production/ consumption, Protecting natural resources (air, land, water), Protecting biodiversity and landscapes, and

c) Social criteria: Increasing consumer welfare, Supporting local communities, Improving health and safety issues, Creating new jobs.

For the expert assessments, a linguistic scale was used (very low, low, medium, high, very high) indicating the importance of each policy instrument in terms of the defined policy objectives. The linguistic scale was further translated into fuzzy sets that, in a next step, were included in a fuzzy multi-criteria decision-making approach PROMETHEE.

IV. Definition of the Fuzzy Membership Function

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 $\tilde{A}$ and in the universe X on the real continuous interval between 0 (non membership) and 1 (complete membership).

The fuzzy number (fuzzy interval) is defined as a fuzzy set 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.

In the presented analysis, the triangular L-R fuzzy number $(m, \alpha, \beta)_{LR}$ was used, represented with the following membership function:

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

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 $\mu_L(x)$). 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

$R(1) = 0$ if $\min_u R(u) = 0$

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

V. Fuzzy Multi-Criteria Approach for Evaluating Biofuels Policies

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) $□_i = \{a_1, a_2, \dots, a_n\}$. 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. Here, the Bellman and Zadeh's [14] max-min operator was used, according to which the decision function D can be expressed as follows:

$$\forall\, a_i \in □,\ D(a_i) = \mathrm{MIN}_j\ \mu_{C_j}(a_i),\ \text{s.t.} (j = 1, 2, \dots, m) \quad (2)$$

As the policy objective is to find the 'best' solution B* that maximizes the decision function D, the decision function has the following form:

$$D(B^*) = \mathrm{M□X}_i \left\{\mathrm{MIN}_j \left[\mu_{C_j}(a_i)\right]\right\},\ \forall\, a_i \in □\ \text{s.t.}\ (i = 1, 2, \dots, n). \quad (3)$$

The multi-criteria problem is expressed as a decision matrix (m×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 (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: [15]).

The weights for each criterion were aggregated, considering the assessments of all ten experts using the arithmetic mean:

$$w_j = \frac{1}{n}\left[\sum_{e=1}^{n} w_j^e\right] = \frac{1}{n}\left[w_j^1 + w_j^2 + \ldots + w_j^{10}\right] \quad (4)$$

where:

w_j – priority weight of the criterion j, $\forall\, j, w_j \in R$, and $j = (1, 2, \ldots, 12)$

n – number of stakeholders, with $n = 10$, and $n = \{e\}$, s.t. $e = (1, 2, \ldots, 10)$.

The fuzzy ratings of each alternative ($⍰_i$, $\forall\, i = 1, 2, \ldots, n$) in terms of each criterion (C_j, $\forall\, j = 1, 2, \ldots, m$) 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:

$$\tilde{x}_{ij} = \frac{1}{n}\left[\sum_{e=1}^{n} \tilde{y}_{ij}^e\right] = \frac{1}{n} \odot \left[\tilde{x}_{ij}^e \oplus \tilde{x}_{ij}^e \oplus \ldots \oplus \tilde{x}_{ij}^e\right] = \left(\frac{1}{n}\sum_{n=1}^{n} x_{ia}, \frac{1}{n}\sum_{n=1}^{n} x_{ib}, \frac{1}{n}\sum_{n=1}^{n} x_{ic}\right) \quad (5)$$

$\tilde{x}_{ij}^e$ – fuzzy rating of the alternative i (a_i) with respect to the criterion j (c_j), $\forall\, i = 1, 2, \ldots, n$ and $\forall\, j = 1, 2, \ldots, m$) for the e[th] 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 $\tilde{d}_j(\tilde{x}_{aj}, \tilde{x}_{bj}) = c_j(\tilde{x}_{aj}) - c_j(\tilde{x}_{bj})$, such that:

$$\tilde{d}_j(\tilde{x}_{aj}, \tilde{x}_{bj}) = [d_j(\tilde{x}_{aj,} \tilde{x}_{bj})^{\alpha}, d_j(\tilde{x}_{aj,} \tilde{x}_{bj})^{m}, d_j(\tilde{x}_{aj,} \tilde{x}_{bj})^{\beta}] \quad (6)$$

Based on the fuzzy difference, the fuzzy preference function $\widetilde{P}_j(a, b)$ was derived measuring the intensity of the total preference for an alternative a compared to an alternative b in the alternative set ⍰. For this study, the V-shape preference function was chosen, such that:

$$\widetilde{P}_j(a, b) = \widetilde{P}_j(\tilde{d}_j) = F_j[\tilde{d}_j(\tilde{x}_{aj}, \tilde{x}_{bj})], \forall\, \tilde{x}_{aj}, \tilde{x}_{bj}, a, b \in ⍰_j \quad (7)$$

and

$$F_j[\tilde{d}_j(\tilde{x}_{aj}, \tilde{x}_{bj})] = P_j(\alpha, m, \beta)_{LR} = (P_j(m) - P_j(m - \alpha);\ P_j(m);\ P_j(m + \beta) - P_j(m)) \quad (8)$$

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

$$\widetilde{\Pi}(a, b) = \frac{\sum_{j=1}^{c_j}[w_j \otimes \widetilde{P}_j(a,b)]}{\sum_{j=1}^{c_j} w_j} = \frac{\sum_{j=1}^{c_j}[(w_j{}^{\alpha}, w_j{}^{m}, w_j{}^{\beta}) \otimes (P_j{}^{\alpha}, P_j{}^{m}, P_j{}^{\beta})]}{\sum_{j=1}^{c_j}(w_j{}^{\alpha}, w_j{}^{m}, w_j{}^{\beta})} \quad (9)$$

$$\widetilde{\Pi}(b, a) = \frac{\sum_{j=1}^{c_j}[w_j \otimes \widetilde{P}_j(b,a)]}{\sum_{j=1}^{c_j} w_j} = \frac{\sum_{j=1}^{c_j}[(w_j{}^{\alpha}, w_j{}^{m}, w_j{}^{\beta}) \otimes (P_j{}^{\alpha}, P_j{}^{m}, P_j{}^{\beta})]}{\sum_{j=1}^{c_j}(w_j{}^{\alpha}, w_j{}^{m}, w_j{}^{\beta})} \quad (10)$$

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 $\tilde{\phi}^{+}(a, b)$ is measuring the strength of all alternatives $a_i \in ⍰$, while the negative flow $\tilde{\phi}^{-}(a, b)$ is measuring the weakness of all alternatives $a_i \in ⍰$:

$$\tilde{\phi}^{+}(a, b) = \sum_{i=1}^{i} \widetilde{\Pi}(a, b), \text{for } \forall\, a_i \in ⍰, \quad (11)$$

$$\tilde{\phi}^{-}(a, b) = \sum_{i=1}^{i} \widetilde{\Pi}(b, a), \text{for } \forall\, a_i \in ⍰ \quad (12)$$

In order to rank the fuzzy flows and to defuzzify the fuzzy numbers, the Yager index was used that is determined by the center of weight of the surface representing its membership function [16]:

$$F(\phi) = \int_0^1 \phi_{\alpha}^{\vee} d\alpha \quad (13)$$

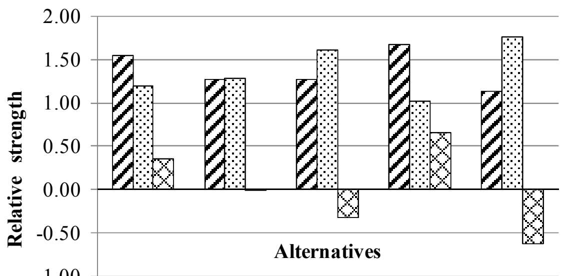
where $\phi_{\alpha}^{\vee}$ is the center (mean value) of the interval ϕ_{α}.

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

VI. Results

A. Base-case scenario

The base-case scenario shows that the distances between the alternative preferences are small, though a clear preference ranking can be indicated. The alternative with the highest preference value is ‘Rural development/ Renewable energy programs’ (a_4) followed by ‘Tax credit’ (a_1), ‘Mandatory blending’ (a_2) and ‘Import tariff barriers’ (a_3). ‘Biofuels quality certification systems’ (a_5) is the least desirable alternative in terms of optimizing decision making in biofuels policies (fig. 1).



	a1	a2	a3	a4	a5
PI+	1.54	1.26	1.27	1.66	1.13
PI-	1.19	1.28	1.6	1.01	1.76
PI Net	0.35	-0.02	-0.33	0.65	-0.63

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

B. Tradeoffs between economic, environmental, and social objectives of the biofuels policy

In order to obtain a balance in policy-making process in terms of meeting several economic, environmental and social criteria simultaneously, all objectives should be weighted equally. However, in the reality of decision making, different objectives have different priorities in regional or national development plans and thus the changing priorities influence the implementation of policy measures.

In this chapter, the impact of changing objective priorities on the ranking of the biofuels policy instruments is shown.

Fig. 2, 3, and 4 display the ranking of the biofuels policies in three different scenarios comparing two policy objectives in a pair-wise process:

1) Objective 1 (economic criteria) with the objective 2 (environmental criteria)
2) Objective 1 (economic criteria) with the objective 3 (social criteria)
3) Objective 2 (environmental criteria) with the objective 3 (social criteria)

The comparison of two objectives provides the advantage of an analysis in a two dimensional space, which facilitates the interpretation of the results.

The comparison was conducted for three situations:

1) 0% importance for the objective 1 and 100% importance for the objective 2,
2) 50% importance for the objective 1 and 50% importance for the objective 2,
3) 100% importance for the objective 1 and 0% importance for the objective 2.

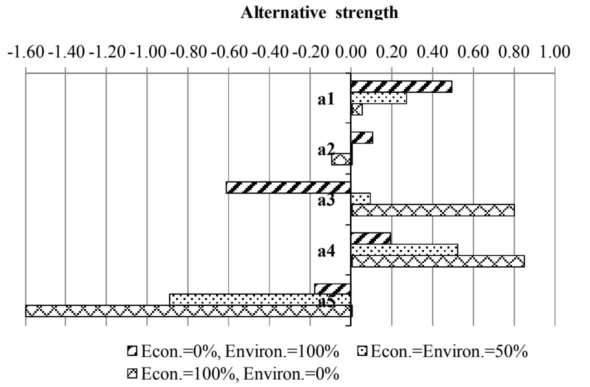


Fig. 2 Tradeoffs between alternatives by changing economic and environmental objectives of biofuels policy

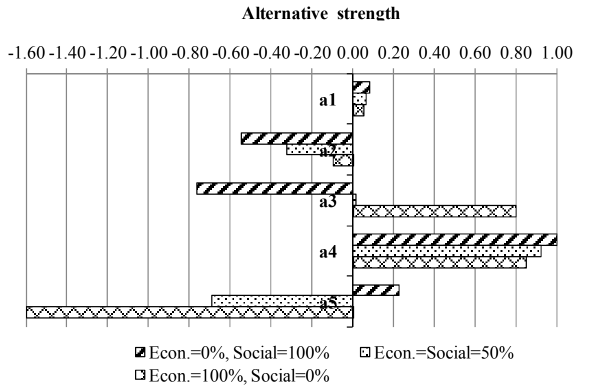


Fig. 3 Tradeoffs between alternatives by changing economic and social objectives of biofuels policy

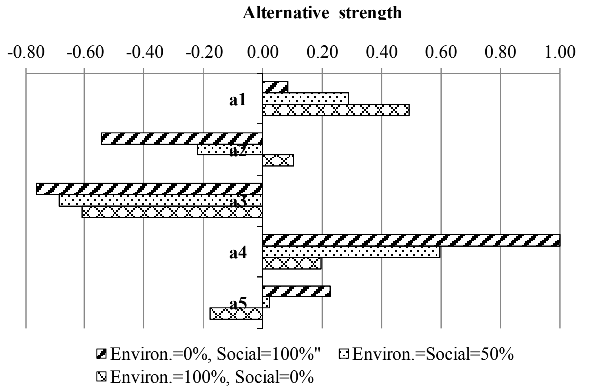


Fig. 4 Tradeoffs between alternatives by changing environmental and social objectives of biofuels policy

When investigating the impact of the economic and environmental objectives on the ranking of the alternatives, the analysis shows that the alternatives a_1, a_4, and a_2 ('Tax credit', 'Rural development/ Renewable energy programs', and 'Mandatory blending') would be preferred in the case when the environmental objectives have the highest possible weight of 100% while the economic objectives have the weight of 0%. The preferences for implementing the alternatives change when economic objectives have the weight of 100%. In this scenario, the most important policy instruments to achieve the economic objectives of the biofuels policy are a_4, a_3, and a_1 ('Rural development/ Renewable energy programs', 'Import tariff barriers', and 'Tax credit'). At the level of an equal importance of the economic and environmental objectives, the alternatives should be implemented in the following sequence to maximize both objectives: a_4, a_1, a_3, a_2, and a_5 (Rural development/ Renewable energy plans → Tax credit → Import tariff barriers → Mandatory blending → Biofuels quality certification systems). In all cases, the alternatives a_4 and a_1 ('Rural development/ Renewable energy programs' and 'Tax credit') have positive net flow values while the alternative a_5 ('Biofuels quality certification systems') has only negative net flow values and is therefore always outranked by other alternatives. This means that this alternative has the lowest importance in terms of maximizing the economic and environmental objectives of the biofuels policy.

Another tendency was found when weighting the economic and social objectives of the biofuels policy. In this case, changing the objective weights has no impact on the alternative a_4 ('Rural development/ Renewable energy programs') despite the given scenarios. As in the first case, the alternatives a_4 and a_1 ('Rural development/ Renewable energy programs' and 'Tax credit') have the positive net flow values and are, therefore, outranking the other alternatives. In the situation when the social objectives of the biofuels policy have the highest importance (100%) while the economic and environmental objectives are not considered, the measures should be implemented as follows: a_4, a_5, a_1, a_2, and a_3 (Rural development/ Renewable energy plans → Biofuels quality certification systems → Tax credit → Mandatory blending → Import tariff barriers). On the contrary, when maximizing the economic objectives, the alternatives a_4 and a_3 ('Rural development/ Renewable energy programs' and 'Import tariff barriers') are the most promising instruments and similarly important in terms of achieving the economic objectives, followed by the alternatives a_1, a_2, and a_5 ('Tax credit', 'Mandatory blending' and 'Biofuels quality certification systems'). At the level of 50% importance given to both the economic and social objectives, the policy instruments should be implemented in the following sequence: a_4, a_1, a_3, a_2, and a_5 (Rural development/ Renewable energy plans → Tax credit → Import tariff barriers → Mandatory blending → Biofuels quality certification systems).

In the third scenario of comparing the environmental and social objectives, at the level of the equal importance of the environmental and social objectives, the most important alternatives with the positive net flow values are a_4, a_1, and a_5, followed by a_2 and a_3 (Rural development/ Renewable energy plans → Tax credit → Biofuels quality certification systems → Mandatory blending → Import tariff barriers).

In each of the analyzed case, the alternatives a_4 and a_1 ('Rural development/ Renewable energy programs' and 'Tax credit') indicate the positive net flow values, while the alternative a_4 is most important in the most analyzed scenarios.

VII. Conclusions

In this paper, a fuzzy algorithm and a fuzzy multi-criteria framework were developed to analyze how missing information, uncertainty of decision making, subjectivity of human assessments can be addressed and included in the evaluation and design process of a sustainable biofuels policy.

In the base-case scenario considering several economic, environmental and social objectives simultaneously, the optimal ranking of the alternatives is as follows: 'Rural development/ Renewable energy programs' (a_4), 'Tax credit' (a_1), 'Mandatory blending' (a_2), 'Import tariff barriers' (a_3), and 'Biofuels quality certification systems' (a_5).

The tradeoff scenarios show the changes in the ranking of the policy instruments depending on preferences given to the respective policy objectives (economic, environmental and social) separately. When comparing the economic and environmental objectives and maximizing the environmental objectives, the alternatives a_1, a_4, and a_2 should be given the preference. In the same comparison scenario, when maximizing the economic objectives, the most important policy instruments are a_4, a_3, and a_1. When comparing the economic and social objectives, and maximizing the social objectives, the policy instruments should be implemented as follows: a_4, a_5, a_1, a_2, and a_3 (Rural development/ Renewable energy plans → Biofuels quality certification systems → Tax credit → Mandatory blending → Import tariff barriers).

In decision-making processes, policy priorities should be clearly defined, depending on regional needs. Those priorities have been included in this framework as scalars. An extension and inclusion of objective weights as fuzzy numbers would allow for considering uncertainties related to weight assessments and policy objectives. However, on the other hand, it would hinder sensitivity analyses necessary to measure the validity of the results.

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