

ANALYSIS OF FACTORS FOR THE ECOLOGICAL AND ECONOMIC SELECTION OF A SETTLEMENT HEAT SUPPLY SYSTEM BASED ON LINGUISTIC INFORMATION

Guliev Jamil Tahir– postgraduate student, department of Heat and Gas Supply and Ventilation, Kyiv National University of Construction and Architecture, Kyiv, Ukraine; AzUAC, camil.quliyev@azmiu.edu.az

Predun Kostiantyn Myronovych– doctor of ec.sci., Professor, Kyiv National University of Construction and Architecture, Kyiv, Ukraine, 31172@ukr.net

Mammadov Nurmammad Yashar– Candidate of Technical Sciences, Professor, AzUAC, Baku, Azerbaijan, nurmammad.mammadov@azmiu.edu.az

Abstract Heat supply systems of settlements are among the largest consumers of fuel and energy resources, which calls for optimizing their structure according to the criteria of energy efficiency and environmental safety. The article proposes a comprehensive mathematical approach to the ecological and economic selection of heat supply systems based on fuzzy logic theory and linguistic variables. A hierarchical model for assessing the influencing factors has been developed; it takes into account the physicochemical properties and cost of fuels, the efficiency of heat generation and heat transportation systems, as well as the specific emission factors of pollutants (CO_2 , NO_x , SO_2 , and particulate matter). To process qualitative expert information, the Mamdani fuzzy inference algorithm (Mamdani FIS) and the centroid defuzzification method (Centroid) were applied. Computer modeling of three heat supply scenarios was carried out in the Python environment. The results showed that the highest integral priority index belongs to the decentralized system based on renewable biomass ($Y^* = 82.4\%$), whereas the traditional centralized natural gas system is characterized by a low priority ($Y^* = 41.2\%$). The scientific novelty lies in the formation of a multicriteria integral index of biosphere compatibility *EESI*, which increases the validity of decisions in the development of heat supply schemes for communities.

Keywords: heat supply systems, fuzzy logic, linguistic variable, defuzzification, Mamdani algorithm, biosphere compatibility, renewable energy sources, decentralization

Introduction. Energy security is one of the main priorities of every state. The housing and utilities sector of Ukraine is currently the country's main consumer of fuel and energy resources (FER) [1]. The sector continues to be dominated by fossil fuels (whose emissions cause significant environmental pollution, especially of atmospheric air), as well as by obsolete technologies and worn-out technical equipment (characterized by low efficiency and, accordingly, low energy efficiency) of energy generation and supply enterprises and of end users — engineering systems, for example, those forming the indoor microclimate of buildings and structures of various purposes [2, 22].

Relevance of the study. Heat supply systems of settlements, which require up to 30% of the country's annual FER volume, are a clear example of this inefficiency. In general, any heat supply system consists of three main structural elements: a heat energy source, heat consumers, and pipelines for transportation.

In accordance with the requirements of the Law of Ukraine “On Heat Supply” [3], the development of heat supply systems of settlements must be based on approved heat supply schemes, which are a pre-design document that substantiates the economic and environmental feasibility and the business necessity of designing and constructing new heat energy sources and heat networks, and of expanding and modernizing existing ones.

In order to save fuel and energy resources and to protect atmospheric air from emissions of pollutants and greenhouse gases, the reconstruction of an existing heat supply scheme or the selection of a new one for a settlement must be based on techno-economic calculations that take into account the optimal combination of centralized, moderately centralized and decentralized (autonomous or individual) heat supply systems, the introduction of energy-efficient technologies, alternative and renewable energy sources, environmental protection, etc., as well as an increase in the operational reliability of technological processes [23, 24]. That is, energy security and climate neutrality no longer contradict each other — they have become interdependent.

The current structure of heat supply systems of Ukrainian settlements was created over decades. Today it is obsolete and, moreover, is on the verge of physical wear-out. Its condition has also been significantly worsened by the uncontrolled switch of the most solvent subscribers to autonomous heat supply. The above realities fully apply to the entire engineering infrastructure of settlements, in particular to the electricity and gas supply systems, which are in municipal ownership and, as a rule, are also unprofitable owing to the mismatch between the tariffs in force and the actual costs of providing the services, and to losses during transportation [1].

Thus, the question arises of determining the ways of further development of engineering support systems of settlements in Ukraine, in particular heat supply systems. This problem becomes even more urgent under martial law. Small towns, as a rule district centers and factory settlements, are in the most difficult situation. The latter received heat from the process boiler houses of industrial enterprises, which in present-day market conditions have become unprofitable and have ceased operating.

Providing the urban community with housing and utility services is one of the main tasks of local self-government bodies. The introduction of alternative types of heating is unaffordable for most residents of a settlement, both financially (a characteristic feature of the subscribers is a high share of socially vulnerable groups with low incomes) and because of the architectural and planning solutions of existing residential buildings (for example, there are no flue ducts for individual heating appliances).

At present, the main problem of heat supply systems is the inefficient use of energy resources, primarily natural gas (the share of “blue fuel” in heat generation by centralized sources is: boiler houses — 97%, CHP plants and thermal power plants — 80%), large heat losses during transportation (the average loss level in main networks is 21.7%), and the high consumer cost for the population (the average level of coverage of economically justified tariffs is 61%: the weighted-average applied tariff is 1452 UAH/Gcal (excluding VAT), and the weighted-average economically justified tariff is 2381 UAH/Gcal (excluding VAT)) [1].

Recent research and publications. In accordance with the Law of Ukraine “On Ratification of the Protocol on the Accession of Ukraine to the Treaty Establishing the Energy Community” [4], our state has undertaken to comply with all decisions and procedural acts adopted in the application of the Treaty. Ukraine has now developed its own legislative framework, and on its basis regulatory and technical documents harmonized with the corresponding European directives and standards have been adopted, aimed at reducing primary energy consumption and, accordingly, pollution of atmospheric air by the combustion products of traditional fuels [3, 12]. Ukraine is a party to the UN Framework Convention on Climate Change (UNFCCC) [13], the Kyoto Protocol [14] and the Paris Agreement [15], which obliges the participating countries to implement long-term low-carbon development strategies (LTS) consistent with the goal of keeping the rise in global temperature well below 2 °C [25]. At the national level, the key legislative act that established the long-term vision of the country's development is the Law of Ukraine “On the Basic Principles of State Climate Policy” [16]. It set the ambitious goal of achieving climate neutrality by 2050, which corresponds to the goals of the European Green Deal (EU Green Deal) [17].

The Long-Term Strategy [8] considers three possible scenarios for achieving climate neutrality, which model different paths of development of Ukraine's economy [26]. In our opinion, the second one is more realistic — “The scenario with additional measures: the scenario includes the implementation of already existing plans, such as the modernization of heat supply and the

improvement of energy efficiency, and additionally provides for the implementation of planned but not yet implemented measures. Under this scenario, emissions can be reduced to 92.0 Mt CO₂-eq. by 2050, or 10.0% of the 1990 level, the base year for assessing environmental pollution when implementing the principles of the Kyoto Protocol.”

The Tax Code of Ukraine establishes tax liabilities for emissions of pollutants and greenhouse gases into atmospheric air [18].

Statement of the objectives of the article. The aim of the article is a comprehensive analysis of the input factors that influence the selection and substantiation of a heat supply system for a settlement, taking into account energy sustainability and biosphere compatibility.

Main part. To create an expert modeling system for the multifactor analysis of the process of accumulation of the factors that influence the choice of a heat supply system for a settlement, a mathematical apparatus based on fuzzy logic theory and the linguistic variable was used [19–21]. This method, as an interconnected set of mathematical models, makes it possible to use expert linguistic information to optimize the choice of a heat supply system for a settlement depending on the factors that determine it. To establish the hierarchical relationships among the factors that influence the choice of a heat supply system, they were classified (Fig. 1).

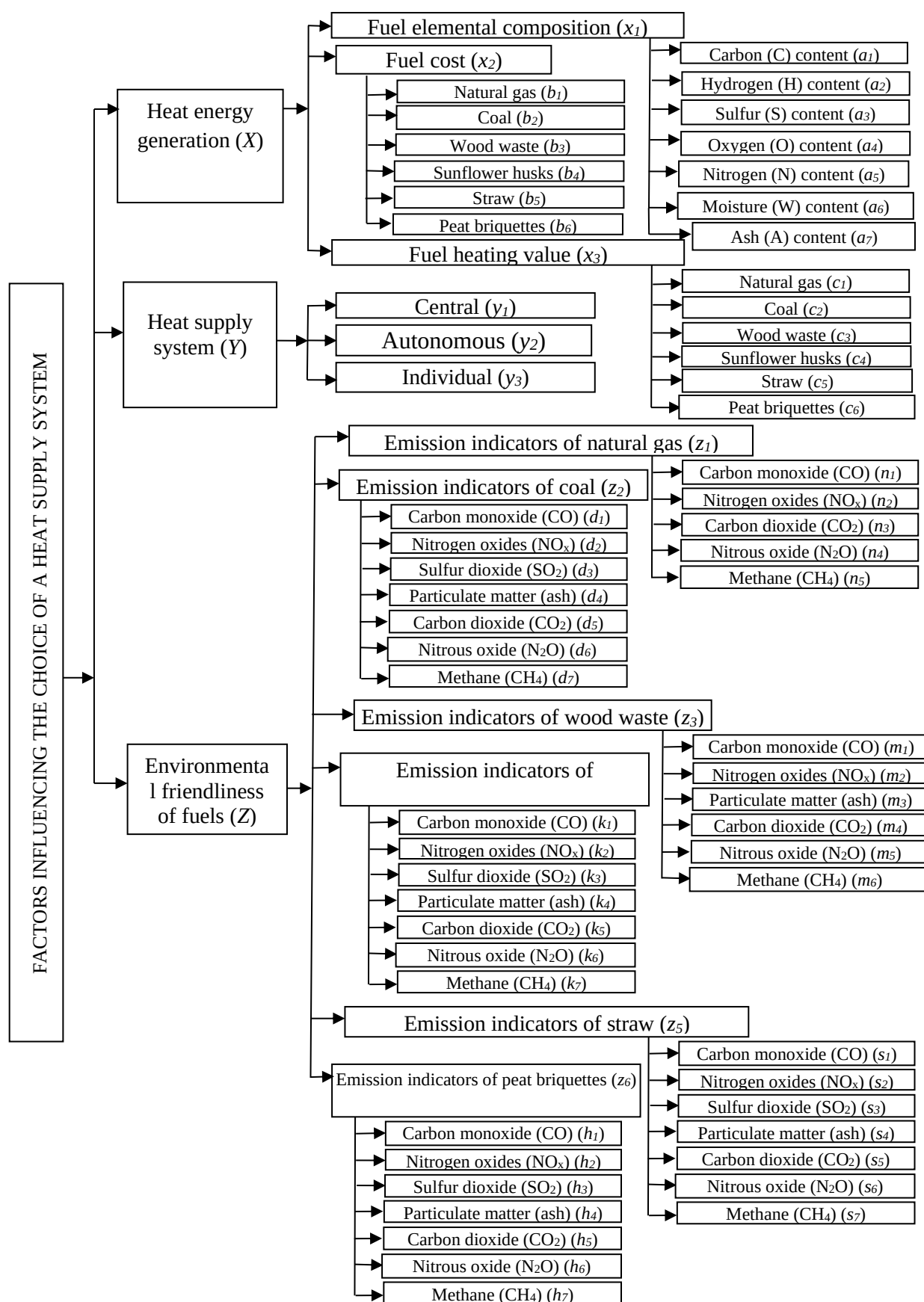


Fig. 1. Classification of the factors influencing the choice of a heat supply system of a settlement

Considering this process at the system level, the linguistic variable A_{HSS} , which characterizes the choice of a heat supply system, can be represented as the relation

$$A_{HSS} = f(X; Y; Z), \quad (1)$$

where X – linguistic variable (LV) describing heat energy generation; Y – LV describing the heat supply system of the settlement; Z – LV describing the environmental friendliness of the fuels used in heat energy generation.

The linguistic variable describing heat energy generation can be represented by the expression

$$X = f(x_1; x_2; x_3), \quad (2)$$

where x_1 – LV “fuel elemental composition”; x_2 – LV “fuel cost”; x_3 – LV “fuel heating value”.

The linguistic variable describing the heat supply system of the settlement can be represented by the expression

$$Y = f(y_1; y_2; y_3), \quad (3)$$

where y_1 – LV “central heat supply system”; y_2 – LV “autonomous heat supply system”; y_3 – LV “individual heat supply system”.

The linguistic variable describing the environmental friendliness of fuels can be represented by the expression

$$Z = f(z_1; z_2; z_3; z_4; z_5; z_6), \quad (4)$$

where z_1 – LV “emission indicators of natural gas”; z_2 – LV “emission indicators of gas coal, grade GR”; z_3 – LV “emission indicators of wood waste, pellets”; z_4 – LV “emission indicators of sunflower husk, pellets”; z_5 – LV “emission indicators of straw, bales”; z_6 – LV “emission indicators of peat briquettes”.

Equation (2) includes the variables x_1, x_2, x_3 , which in turn depend on other factors

$$x_1 = f(a_1; a_2; a_3; a_4; a_5; a_6; a_7); \quad (5)$$

$$x_2 = f(b_1; b_2; b_3; b_4; b_5; b_6); \quad (6)$$

$$x_3 = f(c_1; c_2; c_3; c_4; c_5; c_6), \quad (7)$$

where a_1 – LV “carbon (C) content”; a_2 – LV “hydrogen (H) content”; a_3 – LV “sulfur (S) content”; a_4 – LV “oxygen (O) content”; a_5 – LV “nitrogen (N) content”; a_6 – LV “moisture (W) content”; a_7 – LV “ash (A) content”; b_1 – LV “natural gas cost”; b_2 – LV “coal cost”; b_3 – LV “wood waste cost”; b_4 – LV “sunflower husk pellet cost”; b_5 – LV “straw cost”; b_6 – LV “peat briquette cost”; c_1 – LV “heating value of natural gas”; c_2 – LV “heating value of coal”; c_3 – LV “heating value of wood waste”; c_4 – LV “heating value of sunflower husk pellets”; c_5 – LV “heating value of straw”; c_6 – LV “heating value of peat briquettes”.

Equation (4) includes the variables $z_1, z_2, z_3, z_4, z_5, z_6$, which in turn depend on other factors:

$$z_1 = f(n_1; n_2; n_3; n_4; n_5); \quad (8)$$

$$z_2 = f(d_1; d_2; d_3; d_4; d_5; d_6; d_7); \quad (9)$$

$$z_3 = f(m_1; m_2; m_3; m_4; m_5; m_6); \quad (10)$$

$$z_4 = f(k_1; k_2; k_3; k_4; k_5; k_6; k_7); \quad (11)$$

$$z_5 = f(s_1; s_2; s_3; s_4; s_5; s_6; s_7); \quad (12)$$

$$z_6 = f(h_1; h_2; h_3; h_4; h_5; h_6; h_7); \quad (13)$$

For the mathematical description of fuzzy sets A , corresponding to the term sets for evaluating the influencing factors, triangular membership functions $\mu_A(x) \in [0,1]$ are used. For an arbitrary parameter $x \in [a, c]$ with the modal value b , the membership function is defined by the expression:

$$\mu_A(x; a, b, c) = \begin{cases} 0, & x \leq a, \\ \frac{x-a}{b-a}, & a < x \leq b, \\ \frac{c-x}{c-b}, & b < x < c, \\ 0, & x \geq c. \end{cases}$$

The knowledge base of the expert system is formed on the basis of the fuzzy production rules of the Mamdani algorithm (Mamdani Fuzzy Inference System):

$$R^{(k)}: \text{IF } x_1 \text{ is } A_1^{(k)} \text{ AND } x_2 \text{ is } A_2^{(k)} \text{ AND } z_1 \text{ is } C_1^{(k)} \text{ THEN } \mathbf{A}_{\text{HSS}} \text{ is } B^{(k)},$$

where $k = 1, \dots, K$ — the number of expert rules; $A_1^{(k)}, A_2^{(k)}, C_1^{(k)}$ — the fuzzy terms of the input variables; $B^{(k)}$ — the fuzzy term of the output variable, the priority of the heat supply system.

For defuzzification (the transition from a fuzzy set to a crisp quantitative priority indicator Y^*) the center of gravity method (Center of Gravity / Centroid Defuzzification) is used:

$$Y^* = \frac{\int_Y y \cdot \mu_B(y) dy}{\int_Y \mu_B(y) dy},$$

where $\mu_B(y)$ — the resulting membership function after accumulation of all rules of the knowledge base.

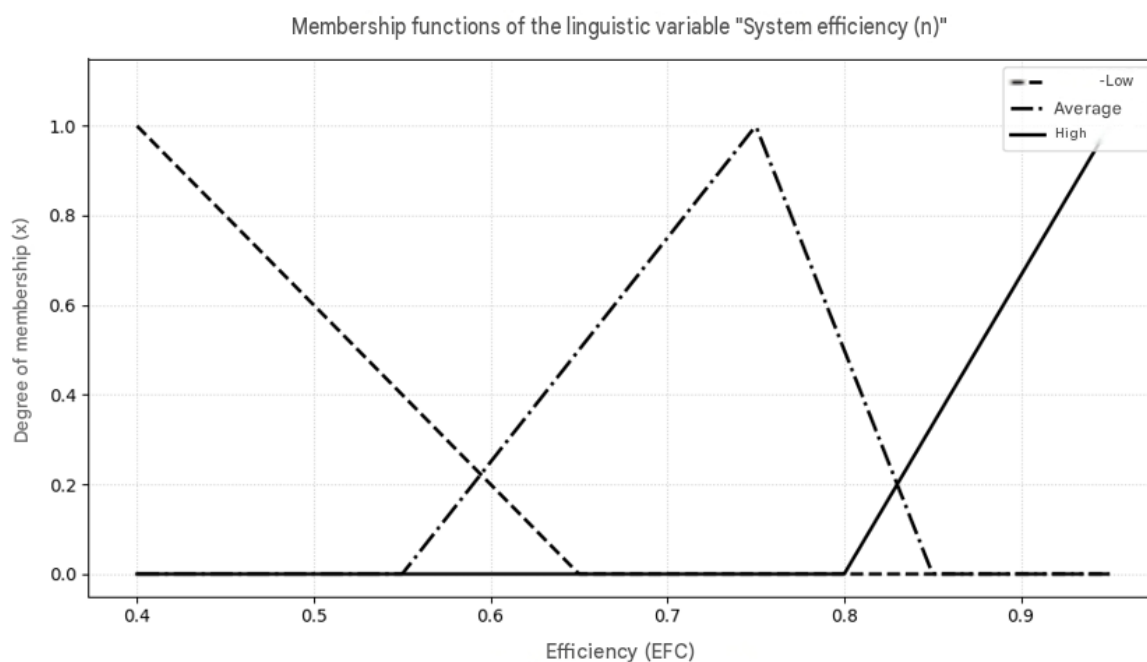


Fig. 2. Graphical representation of the triangular membership functions for the linguistic variable “efficiency of the heat supply system”

The values of the linguistic variables given in relations (1)–(13) are evaluated using a system of qualitative terms specified in the table. The value of the linguistic variable “choice of the heat supply system (degree of priority)” is represented by the following evaluation terms: L — low; bM — below medium; M — medium; aM — above medium; H — high. Each of these terms is a corresponding fuzzy set, which is a certain property considered as a linguistic term. The evaluation terms for the linguistic variables are given in the table.

For the factors influencing the choice of a heat supply system for a settlement, the universes of discourse were selected in accordance with information on:

- the cost of traditional and alternative fuels;
- the physicochemical properties of fuels;
- the calculated emission factors of pollutants and greenhouse gases formed during fuel combustion;
- tax liabilities for environmental pollution;
- the technical characteristics of heat supply systems.

Table 1. Influencing factors as linguistic variables

Designation and name of the variable	Universe of discourse	Terms for evaluation
1	2	3
a_1 – carbon (C) content	30...90%	low (L), medium (M), high (H)
a_2 – hydrogen (H) content	3...25%	low (L), medium (M), high (H)
a_3 – sulfur (S) content	0...6%	low (L), medium (M), high (H)
a_4 – oxygen (O) content	0...30%	low (L), medium (M), high (H)
a_5 – nitrogen (N) content	0.5...2%	low (L), medium (M), high (H)
a_6 – moisture (W) content	0...30%	low (L), medium (M), high (H)
a_7 – ash (A) content	0...40%	low (L), medium (M), high (H)
b_1 – cost of natural gas	0.23...0.29 UAH/MJ	low (L), medium (M), high (H)
b_2 – cost of coal	0.4...1.0 UAH/MJ	low (L), medium (M), high (H)
b_3 – cost of wood waste	0.8...1.0 UAH/MJ	low (L), medium (M), high (H)
b_4 – cost of sunflower husk pellets	0.34...0.73 UAH/MJ	low (L), medium (M), high (H)
b_5 – cost of straw	0.06...0.29 UAH/MJ	low (L), medium (M), high (H)
b_6 – cost of peat briquettes	0.75...1.0 UAH/MJ	low (L), medium (M), high (H)
c_1 – heating value of natural gas	43...48 MJ/kg	low (L), medium (M), high (H)
c_2 – heating value of coal	25...30 MJ/kg	low (L), medium (M), high (H)
c_3 – heating value of wood waste	12...18 MJ/kg	low (L), medium (M), high (H)
c_4 – heating value of sunflower husk pellets	15...20 MJ/kg	low (L), medium (M), high (H)
c_5 – heating value of straw	15...16 MJ/kg	low (L), medium (M), high (H)
c_6 – heating value of peat briquettes	12...14 MJ/kg	low (L), medium (M), high (H)
y_1 – central heat supply system (effective efficiency)	0.48...0.55	very low (VL), low (L), medium (M), high (H), very high (VH)
y_2 – autonomous heat supply system (effective efficiency)	0.75...0.8	very low (VL), low (L), medium (M), high (H), very high (VH)
y_3 – individual heat supply system (effective efficiency)	0.85...0.9	very low (VL), low (L), medium (M), high (H), very high (VH)
n_1 – emission factor of carbon monoxide (CO) from natural gas	17...51 g/GJ	low (L), medium (M), high (H)
n_2 – emission factor of nitrogen oxides (NO _x) from natural gas	42...126 g/GJ	low (L), medium (M), high (H)

n_3 – emission factor of carbon dioxide (CO ₂) from natural gas	58593...175779 g/GJ	low (L), medium (M), high (H)
n_4 – emission factor of nitrous oxide (N ₂ O) from natural gas	0.1...0.3 g/GJ	low (L), medium (M), high (H)
n_5 – emission factor of methane (CH ₄) from natural gas	1...3 g/GJ	low (L), medium (M), high (H)
d_1 – emission factor of carbon monoxide (CO) from coal	121...363 g/GJ	low (L), medium (M), high (H)
d_2 – emission factor of nitrogen oxides (NO _x) from coal	123...369 g/GJ	low (L), medium (M), high (H)
d_3 – emission factor of sulfur dioxide (SO ₂) from coal	2808...8424 g/GJ	low (L), medium (M), high (H)
d_4 – emission factor of particulate matter (ash) from coal	4263...12789 g/GJ	low (L), medium (M), high (H)
d_5 – emission factor of carbon dioxide (CO ₂) from coal	126293...378879 g/GJ	low (L), medium (M), high (H)
d_6 – emission factor of nitrous oxide (N ₂ O) from coal	1.4...4.2 g/GJ	low (L), medium (M), high (H)
d_7 – emission factor of methane (CH ₄) from coal	1...3 g/GJ	low (L), medium (M), high (H)
m_1 – emission factor of carbon monoxide (CO) from wood waste	121...363 g/GJ	low (L), medium (M), high (H)
m_2 – emission factor of nitrogen oxides (NO _x) from wood waste	50...150 g/GJ	low (L), medium (M), high (H)
m_3 – emission factor of particulate matter (ash) from wood waste	87...261 g/GJ	low (L), medium (M), high (H)
m_4 – emission factor of carbon dioxide (CO ₂) from wood waste	105328...315984 g/GJ	low (L), medium (M), high (H)
m_5 – emission factor of nitrous oxide (N ₂ O) from wood waste	1.4...4.2 g/GJ	low (L), medium (M), high (H)
m_6 – emission factor of methane (CH ₄) from wood waste	1...3 g/GJ	low (L), medium (M), high (H)
k_1 – emission factor of carbon monoxide (CO) from sunflower husk pellets	121...363 g/GJ	low (L), medium (M), high (H)
k_2 – emission factor of nitrogen oxides (NO _x) from sunflower husk pellets	50...150 g/GJ	low (L), medium (M), high (H)
k_3 – emission factor of sulfur dioxide (SO ₂) from sunflower husk pellets	159...477 g/GJ	low (L), medium (M), high (H)
k_4 – emission factor of particulate matter (ash) from sunflower husk pellets	191...573 g/GJ	low (L), medium (M), high (H)
k_5 – emission factor of carbon dioxide (CO ₂) from sunflower husk pellets	81320...243960 g/GJ	low (L), medium (M), high (H)
k_6 – emission factor of nitrous oxide (N ₂ O) from sunflower husk pellets	1.4...4.2 g/GJ	low (L), medium (M), high (H)
k_7 – emission factor of methane (CH ₄) from sunflower husk pellets	1...3 g/GJ	low (L), medium (M), high (H)
s_1 – emission factor of carbon monoxide (CO) from straw	121...363 g/GJ	low (L), medium (M), high (H)
s_2 – emission factor of nitrogen oxides (NO _x) from straw	50...150 g/GJ	low (L), medium (M), high (H)

s_3 – emission factor of sulfur dioxide (SO ₂) from straw	121...363 g/GJ	low (L), medium (M), high (H)
s_4 – emission factor of particulate matter (ash) from straw	437...1311 g/GJ	low (L), medium (M), high (H)
s_5 – emission factor of carbon dioxide (CO ₂) from straw	99278...297834 g/GJ	low (L), medium (M), high (H)
s_6 – emission factor of nitrous oxide (N ₂ O) from straw	1.4...4.2 g/GJ	low (L), medium (M), high (H)
s_7 – emission factor of methane (CH ₄) from straw	1...3 g/GJ	low (L), medium (M), high (H)
h_1 – emission factor of carbon monoxide (CO) from peat briquettes	121...363 g/GJ	low (L), medium (M), high (H)
h_2 – emission factor of nitrogen oxides (NO _x) from peat briquettes	50...150 g/GJ	low (L), medium (M), high (H)
h_3 – emission factor of sulfur dioxide (SO ₂) from peat briquettes	332...996 g/GJ	low (L), medium (M), high (H)
h_4 – emission factor of particulate matter (ash) from peat briquettes	1893...5679 g/GJ	low (L), medium (M), high (H)
h_5 – emission factor of carbon dioxide (CO ₂) from peat briquettes	93278...279834 g/GJ	low (L), medium (M), high (H)
h_6 – emission factor of nitrous oxide (N ₂ O) from peat briquettes	1.4...4.2 g/GJ	low (L), medium (M), high (H)
h_7 – emission factor of methane (CH ₄) from peat briquettes	1...3 g/GJ	low (L), medium (M), high (H)

For a comprehensive ecological and economic assessment of the efficiency of heat supply systems, a multicriteria integral index of biosphere compatibility and energy efficiency (*EESI*):

$$EESI = w_1 \cdot \eta_{sys} + w_2 \cdot \left(\frac{C_{min}}{C_{fuel}} \right) + w_3 \cdot \left(\frac{E_{min}}{E_{total}} \right),$$

where η_{sys} — effective efficiency of the system; C_{fuel} — fuel cost (UAH/MJ); C_{min} — minimum cost among the fuel types analyzed; E_{total} — total environmental impact of emissions; $w_1, w_2, w_3 \in [0,1]$ — weighting coefficients of the criteria ($\sum_{i=1}^3 w_i = 1$), determined by the analytic hierarchy process (AHP).

The total environmental impact of emissions E_{total} is calculated taking into account the relative toxicity of the components:

$$E_{total} = e_{CO_2} + \alpha \cdot e_{NO_x} + \beta \cdot e_{SO_2} + \gamma \cdot e_{PM},$$

where e_i — emission factor of the i -th pollutant (g/GJ); α, β, γ — coefficients of the relative environmental hazard of pollutants with respect to carbon dioxide (CO₂).

Results and discussion. On the basis of the developed mathematical apparatus, computer modeling was performed in the Python environment using the scikit-fuzzy library. A comparative analysis of three scenarios of organizing the heat supply of a settlement was carried out:

1. Centralized natural gas system ($\eta = 0.52$, fuel cost 0.26 UAH/MJ, high emission level of CO₂).
2. Decentralized (autonomous) wood pellet system ($\eta = 0.78$, fuel cost 0.80 UAH/MJ, neutral balance of CO₂, increased particulate matter emissions).
3. Individual straw/biomass system ($\eta = 0.88$, fuel cost 0.18 UAH/MJ, low environmental toxicity).

Based on the results of defuzzification by the center of gravity method, the following crisp values of the integral priority index Y^* were obtained:

- Centralized system (gas): $Y^* = 41.2\%$ (category “below medium”);
- Autonomous system (pellets): $Y^* = 68.5\%$ (category “above medium”);

- Individual/local system (biomass/straw): $Y^* = 82.4\%$ (category “high”).

The obtained results confirm the high sensitivity of the developed fuzzy model to changes in cost and environmental factors and prove the advisability of the transition to moderately decentralized systems based on renewable biomass.

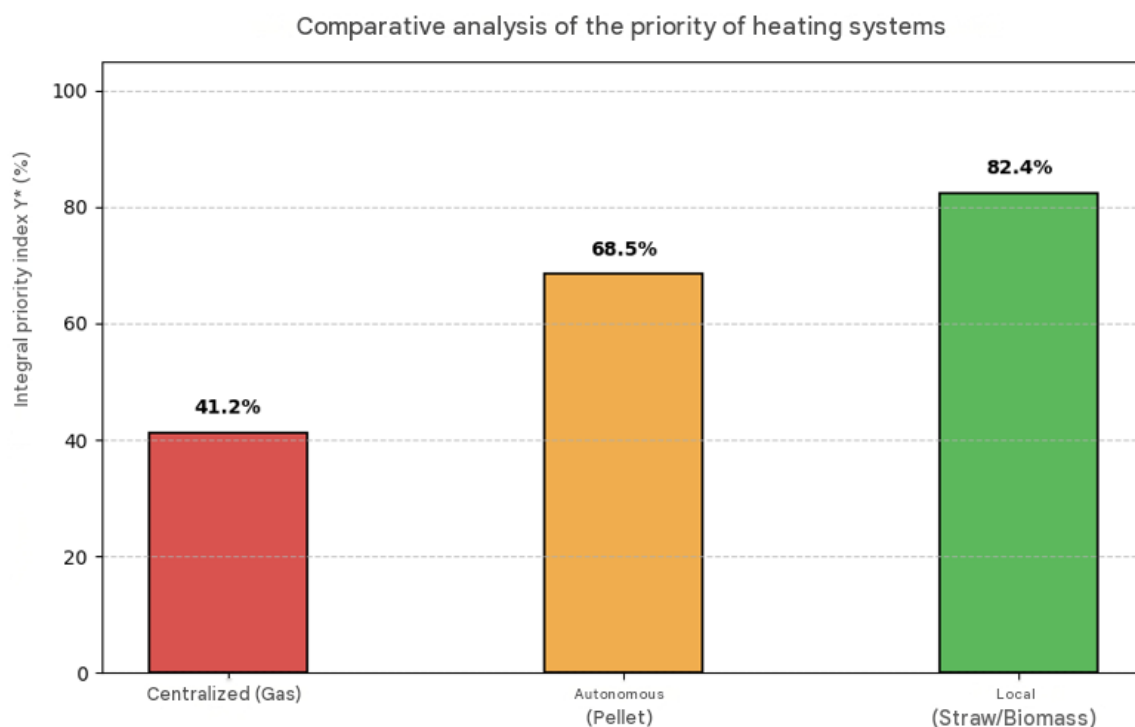


Fig. 3. Comparative results of the assessment of the integral priority index (Y^*) of heat supply systems for the three baseline scenarios

Conclusions.

1. An improved mathematical apparatus based on fuzzy logic theory and the Mamdani algorithm has been proposed for the multicriteria analysis and substantiation of the choice of a heat supply system for a settlement, taking into account biosphere compatibility factors.
2. An extended system of linguistic variables and their triangular membership functions has been formed, covering techno-economic indicators (efficiency, fuel cost) and environmental indicators (specific emissions of CO_2 , NO_x , SO_2 , and particulate matter).
3. A multicriteria integral index $EESI$ has been developed, which makes it possible to comprehensively assess the environmental and economic effects of introducing renewable energy sources.
4. The results of computer modeling showed that the highest integral priority index ($Y^* = 82.4\%$) belongs to the decentralized biomass/straw system, which confirms the advisability of a gradual move away from traditional centralized gas-based heat supply ($Y^* = 41.2\%$) in favor of local renewable sources.

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