



Original Research Article

Fuzzy Decision Model for Prioritising Environmentally Harmful Boiler Decommissioning

Dejan Ivezic^{*1}, Miloš Tanasijević¹, Marija Živković¹, Aleksandar Madžarević¹, Boban Pavlović¹, Dejan Stojanović²

¹University of Belgrade, Faculty of Mining and Geology, Belgrade, Serbia

²District Heating Business Association "Toplane Srbije", Šabac, Serbia

e-mail: dejan.ivezic@rgf.bg.ac.rs, milos.tanasijevic@rgf.bg.ac.rs, marija.zivkovic@rgf.bg.ac.rs,
aleksandar.madzarevic@rgf.bg.ac.rs, boban.pavlovic@rgf.bg.ac.rs, boban.pavlovic@rgf.bg.ac.rs

Cite as: Ivezic, D., Tanasijević, M., Živković, M., Madžarević, A., Pavlović, B., Stojanović, D., Fuzzy Decision Model for Prioritising Environmentally Harmful Boiler Decommissioning, *J.sustain. dev. energy water environ. syst.*, 14(2), 1140682, 2026, DOI: <https://doi.org/10.13044/j.sdewes.d14.0682>

ABSTRACT

Environmentally harmful boiler rooms that use coal and liquid fuels (heavy fuel oil and heating oil) remain in operation across Serbian cities, either as parts of centralised systems or as stand-alone units. Although they significantly degrade air quality, their decommissioning is often delayed because feasibility studies indicate unfavourable financial outcomes. While greenhouse gas emissions can be monetised through emission trading schemes, no widely accepted method exists for valuing local air pollution in investment assessments. This paper proposes a fuzzy decision-making model that integrates financial, climate, and environmental criteria to support fuel-switching and decommissioning decisions. The model evaluates pollutant reductions, investment needs, and payback periods, converts them to fuzzy linguistic variables, and applies max–min composition for overall prioritisation. A case study of 25 boiler rooms in six Serbian cities demonstrates the approach. Results show that including environmental indicators highlights projects with substantial ecological benefits that would otherwise be overlooked under purely financial assessments.

KEYWORDS

Fuel switch, Heating, District heating system, Renewable energy sources, Decision-making, Fuzzy model.

INTRODUCTION

Urban heating systems, particularly those relying on fossil fuel combustion, are a significant source of local air pollution in cities. District heating plants and individual boilers emit particulate matter (PM), nitrogen oxides (NO_x), and sulphur dioxide (SO₂), which contribute to poor air quality and adverse health impacts [1]. Transitioning to cleaner heating technologies and increasing the share of renewable heat can substantially reduce urban air pollution and associated health risks [2].

Obsolete coal and fuel oil-fueled boiler rooms, which are the subject of this research, are located mainly in the inner-city centres in highly populated areas in Serbia and represent a significant source of emission of NO_x, SO₂, particulates (PM_{2.5}, PM₅, PM₁₀), CO, soot, etc. [3], especially during the heating season [4]. Together with other sources of air pollution and

^{*} Corresponding author

unfavourable weather conditions, these boiler rooms cause poor air quality in Serbian cities during heating seasons.

Projects for decommissioning harmful boilers are mostly very capital-intensive. In situations where limited resources must be allocated among different decommissioning projects for harmful boiler houses, it is important to establish clear criteria for project prioritisation. This situation is not a problem when the entire design process is conducted (including feasibility studies, preliminary design, detailed design, and environmental and social impact assessments). In that case, a wide range of indicators of project feasibility is available, a comprehensive analysis of all projects across technical, financial, environmental, and social aspects is possible [5], and conclusions about project feasibility can be drawn relatively easily [6].

However, the challenge is significantly greater in the early planning phase, when a relatively large number of potential projects must be screened and compared, often based on limited, incomplete, or uncertain information. At this stage, conducting full feasibility studies for all candidate projects is neither practical nor economically justified. Nevertheless, decisions still need to be made on which projects should advance to the following stages of development. There is a clear need for a simple, transparent, and methodologically sound evaluation framework that can support early-stage decision-making and project ranking [7].

In this context, the consideration of a broader set of influential criteria is widely used in urban sustainability assessments and in the evaluation and ranking of urban energy projects [8]. In this regard, researchers often seek solutions that enable the simultaneous consideration of multiple, often conflicting, criteria. According to [9], a review of the literature shows that investment cost is the most frequently used criterion in energy project evaluation, as it directly determines financial feasibility, and CO₂ emissions follow closely, given the increasing importance of climate goals and environmental protection. In another study on energy projects [10], the most important indicators are related to technical performance, especially system efficiency, which leads to emission reductions and, in turn, to better economic outcomes. Similar conclusions were reported in [11], where efficiency, investment cost, and CO₂ emissions were identified as the key technical, economic, and environmental criteria. Based on [12], investment and operating costs were ranked as the most significant factors in technology selection, and other criteria of lower importance included comfort, CO₂ emissions, commercial maturity, and economic development in a specific local context. Comparable findings were also reported in [13], where economic viability was identified as the dominant factor, alongside environmental benefits, job creation, and local context, such as the use of domestic resources, social and policy relevance, and community needs.

A review of the existing literature shows that a similar core set of evaluation criteria is often applied, while different decision-support methods are used, with methodological adjustments to better capture local conditions and project-specific characteristics [14]. In practice, these methods are frequently "tuned" to reflect the local context, including existing infrastructure, available technologies, regulatory frameworks, environmental constraints, and the socio-economic characteristics of the area [15]. As a result, both the selection of evaluation criteria and the definition of feasible alternatives are tailored to the local context and specific technological and environmental challenges, particularly in cases involving outdated, environmentally harmful heat production facilities.

The reviewed studies consistently highlight the need for problem-specific, context-sensitive ranking frameworks rather than universal or purely generic approaches. Such tailored methodologies allow decision-makers to structure and justify project prioritisation in a transparent and reproducible manner, even at early stages of planning, thereby strengthening the credibility and effectiveness of investment decisions in urban energy transition processes.

Starting from the above premises, the proposed methodology aims to establish a structured, transparent approach to the early-stage evaluation and prioritisation of boiler room decommissioning projects. The methodology incorporates all key elements of the standard

design procedure; however, these elements are systematically organised and condensed to enable a fast, consistent comparison of a large number of projects under limited data availability [14].

The core of the methodology is the introduction of environmental efficiency indicators, used in combination with financial indicators in the decision-making process to rank projects for further development. Given the early phase of project preparation, these indicators should be interpreted as expected or most probable values, derived from reasonable assumptions and design simplifications, rather than as exact or final design outcomes.

To explicitly address the uncertainty inherent in such early-stage assessments, a dedicated Fuzzy Decision-Making (FDM) model [16] is introduced to compare and rank alternative project solutions for the decommissioning of environmentally harmful boiler rooms. Fuzzy inference systems use logical rules, making them flexible and adaptable to various contexts [17], including situations with uncertain, incomplete, or unclear information [18]. They are very useful because they allow the processing of complex information in a way similar to human reasoning [19].

As a case study, 25 boiler rooms fueled by coal, heavy fuel, or heating oil in six Serbian cities (Belgrade, Niš, Užice, Valjevo, Novi Pazar, and Smederevo) are considered [20]. The current emissions of pollutants (SO₂, NO_x, and particulate matter) and greenhouse gases (GHGs) for each boiler room are calculated and presented. The solutions for boiler room decommissioning are then proposed. The analysed decommissioning options are politically and institutionally relevant solutions, aligned with the national planning and regulatory framework aimed at reducing air pollution, mitigating climate change impacts, and improving energy efficiency in the heating sector. The environmental effects (reduction of pollutant emissions) and climate impacts (reduction of GHG emissions) of the proposed boiler room decommissioning are assessed, and the corresponding indicators of environmental efficiency are calculated. In addition to these, key financial parameters, such as the cost of produced thermal energy, are calculated, and the simple payback period for each case, along with the cost of emission reduction associated with boiler room decommissioning, are explicitly presented. Finally, project prioritisation is performed using the Fuzzy Decision-Making model, based on a combined evaluation of actual values and expected ranges of simple payback periods, relative emission reductions, and relative costs of emission reduction.

PROCEDURE FOR SELECTING A PROJECT SOLUTION FOR DECOMMISSIONING HARMFUL BOILER ROOMS

The procedure for selecting project solutions for harmful boiler room decommissioning has two phases. The first phase involves a classical engineering approach in determining project solutions. The procedure is based on a current-state analysis and identification of available "new" energy sources, followed by the definition of new technical concepts/options for using selected sources. Assessment of environmental benefits and financial analysis of the proposed concept are completed by determining financial and environmental indicators for each project solution.

- Description of the current situation – Baseline Data Collection. Baseline Data include basic technical and operational characteristics of the selected boiler rooms, energy production, and consumer characteristics. Data should be collected for the last few heating seasons. To avoid the effects of unusually cold or warm years, the series should include at least the last three heating seasons. Using these data, energy efficiency indicators, as well as average GHG and pollutant emissions for at least the last three heating seasons, are calculated. In addition, the current operational cost of energy production is calculated based on fuel costs only. The collected data, along with the calculated data based on them, are presented in **Table 1**.

Table 1. Baseline Data for a selected boiler room

Collected		Calculated	
Basic technical and operation characteristics	Total heat power [kW]	Production and efficiency	Energy production [kWh]
	Heat power of single boiler units [kW]		Efficiency of consumption [kWh/m ² /year, kWh/m ² /HDD]
	Operation regime [°C/°C]	Emission of GHG [kg]	CO ₂
	Efficiency of boilers		CH ₄
	Operation period [h/year]		N ₂ O
	Type of fuel		CO ₂ eq
	Annual fuel consumption		
Consumers characteristics	Area of heated residential space [m ²]	Pollutants emissions [kg]	NO _x
	Area of heated commercial space [m ²]		SO ₂
	Heating degree days		CO
Cost of energy production [EUR/kWh]			

- Identification and assessment of available energy inputs include consideration of energy sources to replace the presently used fossil fuels. Acceptable sources of energy include district heating networks and renewable energy sources. Use of natural gas in boiler houses is acceptable only in combination with renewables, when RES will cover the base load, and natural gas will be used to cover peak demand. Therefore, in this phase, the location and description of the district heating network, available renewable energy sources, and, in some cases, the natural gas network are considered.
- Technical concepts/options for the new heating source include, inter alia, the general scheme(s) of the proposed technological option(s) [21], heat power of the new heating source(s), energy efficiency of the new heating source(s) [22], thermal storage size (if necessary), sources and amount of substitute energy/RES, heat power of backup and peak facilities (if required) [13], as well as all other characteristics needed for understanding of new system operation.
- Assessment of environmental benefits is obtained by calculating the annual GHG and pollutant emissions from new heat sources and the reduction in emissions compared to the present state. The greenhouse gases considered are carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O). In calculations, these GHGs are introduced as CO₂ equivalents, calculated using their global warming potentials [23]. The pollutants considered are sulphur dioxide (SO₂), nitrogen oxides (NO_x), carbon monoxide (CO), and particulate matter (PM). Their emissions are calculated based on the annual fuel consumption, the lower heating value of fuels, and corresponding emission factors. The emission factors are taken from the literature [24].
- The financial analysis of proposed concepts presents a rough financial analysis of different projects, including, inter alia, a cost table that provides the best estimates of the costs of technical concept realisation and the expected operational fuel expenditure for each proposed technical concept. The benefit of this approach is that it allows defining the break-even point for each project using costs per unit of used energy, enabling comparison of their quality [25].

- The calculation of indicators, environmental benefits, financial analyses, and the carbon trade potential of proposed concepts for decommissioning environmentally harmful boiler rooms serves as the basis for further project development activities. In the decision-making process, it is helpful to have indicators that integrate different aspects of projects as follows.

Simple payback period (*SP*) indicator: The financial benefit of the project, including GHG reduction; it is calculated as the ratio of investment costs in a new heat source and the reduction in operating and GHG emission costs due to the introduction of a new heat source, see eq. (1):

$$SP = \frac{CoI}{(CoES - CoNS) + CoGHG} \text{ [year]} \quad (1)$$

Where: *CoI* [EUR] is the cost of investments in the new heat source – the investment cost includes the cost of a new RES-based facility (heat pump, biomass boiler, solar collectors, etc.) or the cost of connecting to the district heating network (cost of a connecting pipeline and heating substation), and in the case of RES use, this cost also includes the cost of a peak boiler and/or heat storage (where necessary). *CoES* [EUR/year] is the annual cost of the existing boiler room operation – it includes only fuel costs. *CoNS* [EUR/year] is the annual cost of the operation of the proposed new facility (for connecting to DHS, the calculation is based on the actual cost of heat production in the existing heating plant, using the energy production calculated and presented in **Table 1**; in the case of RES, this cost includes energy costs, i.e., electricity costs for heat pump operation, biomass costs, natural gas costs for peak boiler operation, etc.; regarding operating costs that are not included – costs of labour, maintenance, etc. – small boiler rooms either remain small in the case of RES use [20], not affecting other operation costs apart from the mentioned energy costs, or they become part of an extensive district heating system where their contribution to other operation costs is marginal, hence negligible [26]. *CoGHG* [EUR/year] is the cost of avoided GHG emissions, calculated as project income, using the CO₂ price in the EU ETS [27].

Relative emission reduction (*RE*) indicator: emissions reduction per unit of thermal power in boiler rooms. It compares the sum of pollutant (NO_x, SO₂, CO, PM) emissions reduction and the heat power of the boiler house that needs to be replaced, see eq. (2) [28]:

$$RE = \frac{EoES - EoNS}{HP} \text{ [kg/MW]} \quad (2)$$

Where: *EoES* [kg] is the sum of annual pollutants (NO_x, SO₂, CO, PM) emissions from the existing boiler room, calculated and presented in **Table 1**. *EoNS* [kg] is the sum of annual pollutants (NO_x, SO₂, CO, PM) emissions from the proposed new facility; in the case of connection to the DHS, this emission is calculated based on the energy production, calculated and presented in **Table 1**, regarding the existing DHS's fuel mix. *HP* [MW] is the thermal power of the boiler house that needs to be replaced. The value of *RE* depends on the fuel being replaced, the energy source that will be used for replacement, the efficiency of heat production before and after, etc. Higher values of this indicator indicate higher environmental efficiency of the proposed solution.

The cost of emission reduction (*CR*) indicator correlates the costs of the proposed solution with the emission reduction, see eq. (3):

$$CR = \frac{CoI}{EoES - EoNS} \text{ [EUR/t]} \quad (3)$$

In general, this indicator could include GHG emissions (EUR/t CO₂eq reduction) [29] and pollutant emissions (EUR/t SO₂+NO_x+PM+CO reduction) [30]. However, here, only an indicator related to pollutant emissions will be used for prioritisation, as GHG emission reductions are included in the calculation of the simple payback period [20].

METHODOLOGY FOR THE EVALUATION AND RANKING OF PROJECT SOLUTIONS – FUZZY DECISION-MAKING MODEL

The traditional approach in multi-criteria decision-making (MCDM) relied on classical (crisp) quantitative methods that assumed precise, deterministic input data and clear boundaries between alternatives. Simple weighted scoring models, Analytic Hierarchy Process, cost-benefit analysis, linear programming, and ELECTRE, among others, were commonly used with exact numerical values and binary logic (true/false, yes/no) [31].

Fuzzy decision models are widely applied within MCDM frameworks to address uncertainty, vagueness, and subjective judgment that often arise when evaluating complex alternatives [17]. Instead of relying on precise numerical inputs, fuzzy approaches use linguistic variables (e.g., low, medium, high) and membership functions to represent imprecise data and expert opinions, enabling a more realistic representation of real-world conditions [32]. In a fuzzy MCDM model, criteria weights, performance ratings, and aggregation procedure can all incorporate fuzzy numbers, allowing decision-makers to compare alternatives even when information is incomplete or ambiguous [33].

The Fuzzy Decision-Making (FDM) model proposed in this paper uses a fuzzy inference engine to transform input indicators into a single overall indicator [34]. The resulting indicator is used in the decision-making process to rank project solutions. An FDM model is selected for ranking project solutions because, in the initial phase of project consideration, most figures related to project financials and subsequent operational parameters are relatively uncertain. The investment costs are evaluated by considering similar realised projects or recommendations of local DH companies. In addition, emission reduction can vary around the average values used for indicator calculation. Therefore, instead of numerical indicator values, FDM used their linguistic interpretation. The model enables classification and grouping of input parameters, with the composition outcome resulting from two-dimensionally defined input parameters based on experience and intuition, in a form that is more flexible and adaptive than other optimisation methods [35].

All input indicators are presented as fuzzy sets (FS), and the outcome of the composition is a fuzzy number (FN). In FDM, the proposition phase involves defining linguistic variables (LVs) and the FS structure (shape and layout). The structure of FS is based on the intuition and experience of experts. By selecting different shapes and layouts, it is possible to represent LV more objectively and achieve greater flexibility in shaping the composition, thus avoiding a linear conclusion model. FN is defined by the membership function (μ) and the unit of measurement (j class) for the observed phenomenon. The general form of a fuzzy number is shown in eq. (4):

$$FN(\mu, j) = \mu_{FN}(j = 1), \mu_{FN}(j = 2), \dots, \mu_{FN}(j = n) \quad (4)$$

Where $\mu \in (0,1)$ is the membership function, and $j = 1 \dots n$ represents the class of the measurement unit. Each j -th class is mapped to the real value of the input indicator. The experts usually define the mapping rules.

There are three input indicators for prioritising boiler rooms for decommissioning: Simple Payback Period (*SP*), Relative Emission Reduction (*RE*), and Costs of Emission Reduction (*CR*). Determining the boundaries and shapes of fuzzy sets for these indicators is a critical step in developing the fuzzy model. Generally accepted thresholds for different levels of investment

profitability (denoted as *SP*), environmental efficiency (denoted as *RE*), and financial efficiency of emission reduction (denoted as *CR*) do not exist. Therefore, for each specific case, it is necessary to carefully analyse the indicator values and classify them into a certain number of characteristic states, taking into account both their absolute values and their relative relationships.

In this paper, based on the authors' experience and the calculated indicator values (presented in the Case Study section), each indicator is represented by four characteristic states, each described as a linguistic variable. A trapezoidal shape of the fuzzy sets was adopted [33]. Trapezoidal boundaries are determined based on the authors' consensus on assigning indicator values to specific linguistic categories. Overlaps between linguistic categories reflect different subjective perceptions of belonging to specific linguistic categories. The following linguistic variables and their boundaries are proposed for each indicator:

- *SP*: Extremely profitable (<5 years), Profitable (4–12 years), Marginally profitable (10–16 years), Unprofitable (>15 years).
- *RE*: Very high reduction (>800 kg/kW), High reduction (400–1000 kg/kW), Reduction (80–500 kg/kW), Minimal reduction (<100 kg/kW).
- *CR*: Very expensive reduction (>2000 EUR/t), Expensive reduction (1000–3000 EUR/t), Moderately expensive reduction (100–1200 EUR/t), Cheap reduction (<200 EUR/t).

Graphical representations of *SP*, *RE*, and *CR* fuzzy sets, linguistic variables, and mapping rules for the connection between indicator values and classes *j* (where *j* = 1 to *n*, and *n* = 10) are presented in Figure 1. This means that each project solution will be represented by three fuzzy numbers $SP(\mu, j)$, $RE(\mu, j)$, and $CR(\mu, j)$, while the assessment of a single solution will be the fuzzy number $PA(\mu, j)$.

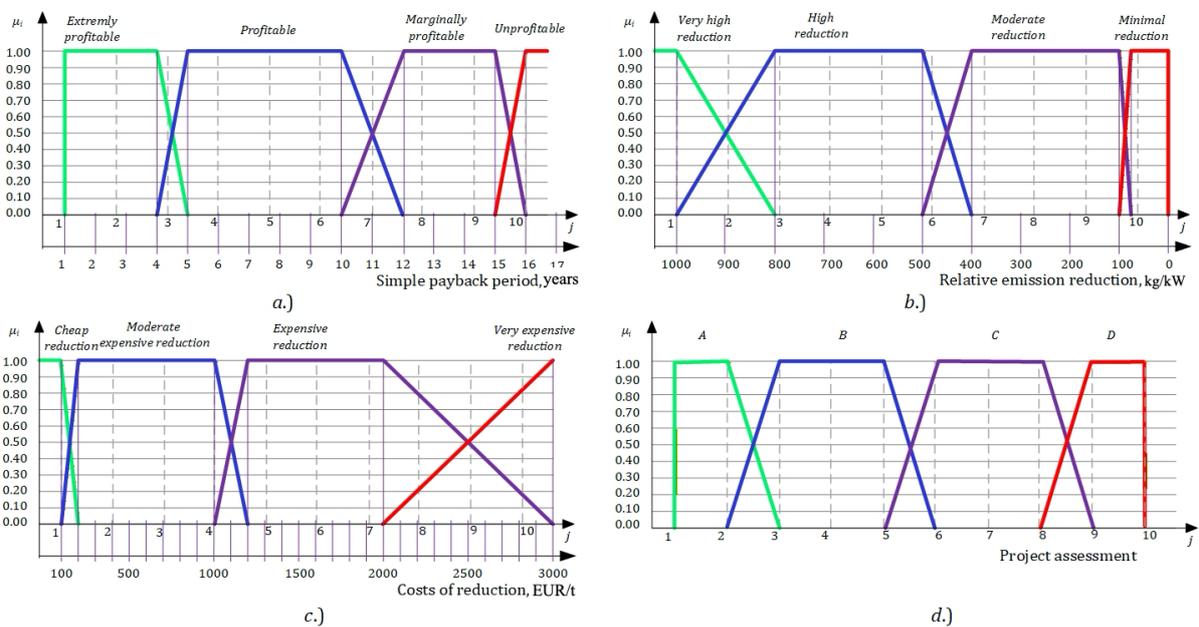


Figure 1. Fuzzy sets, linguistic variables, and mapping rules for: simple payback period (a), relative emission reduction (b), cost of reduction (c), and project assessment (d)

If the boundaries defining the linguistic variables were to change, this would have an impact on the project assessment of a specific project only if one of the membership functions of its indicators were to change (e.g., changing the boundaries would cause a "profitable" project to become "marginally profitable" or "extremely profitable"). However, if the membership function of the selected indicator remains unchanged as the boundaries of the linguistic values change, the project assessment will not change. It is important to note that the

project assessment does not depend on the absolute boundaries of the linguistic values, but rather on the shape and the values of the membership functions at the points relevant to the specific project.

Fuzzy composition represents the operation of combining multiple fuzzy relations [36]. In fuzzy algebra, the most used operations are max-min and min-max. The first is used in decision-making and optimisation processes, while the second is used in risk analysis. In the observed example of boiler room decommissioning prioritisation, the max-min composition is used [37].

Let: $SP(\mu, j)$, $RE(\mu, j)$, and $CR(\mu, j)$ be the three FNs representing project indicators. The max-min composition is defined as FN, obtained as Cartesian products of indicators FNs (eq. (5), eq. (6), and eq. (7)):

$$PA = SP \circ RE \circ CR = \mu_{PA}(j = 1), \dots, \mu_{PA}(j = n) = MX(j = 1), \dots, MX(j = n) \quad (5)$$

Where:

$$MX(j) = \max_j \{MN_{O=j} \mu(SP) \wedge MN_{O=j} \mu(RE) \wedge MN_{O=j} \mu(CR)\}, \text{ for all } j=1 \dots n \quad (6)$$

$$MN_{O=j} \mu(SP, RE, CR) = \min_{O=j} \{\mu(SP, RE, CR)_j\}, \text{ for } j = O \quad (7)$$

The outcome O is an integer rounded value that is determined for any combination of input parameters $c = j$ (eq. (8)):

$$O_c = ((j_{SP})_c + (j_{RE})_c + (j_{CR})_c) / 3 \quad (8)$$

Such membership functions could create $C = n^3$ mutual combinations, varying all three indicators and class j . Each combination represents a possible input to the project assessment (PA), see eq. (9).

$$PA_c = (\mu_{SP, RE, CR})_{c=1 \dots C} = (\mu_{SP}^{j=1 \dots n}, \mu_{RE}^{j=1 \dots n}, \mu_{CR}^{j=1 \dots n}), \text{ for all } c = 1 \dots C \quad (9)$$

To analyse individual projects, it is necessary to transform relationship (9), using the best-fit identification method, into eq. (10) [36].

$$PA = (\mu(j=1), \dots, \mu(j=n)) \rightarrow PA = (\mu(A), \mu(B), \mu(C), \mu(D)) \quad (10)$$

Where the marks A , B , C , and D represent the LV for Project Assessment: Highly Acceptable Project, Very Acceptable Project, Acceptable Project, and Low Acceptable Project, respectively.

For easier comparative analysis of the obtained results for various projects, the horizontal coordinate of the 'centre of mass' of fuzzy number (10) will be calculated and accepted as the project score, eq. (11) [16]:

$$Z(PA) = \frac{\mu(A) \cdot X_{C-A} + \mu(B) \cdot X_{C-B} + \mu(C) \cdot X_{C-C} + \mu(D) \cdot X_{C-D}}{\mu(A) + \mu(B) + \mu(C) + \mu(D)} \quad (11)$$

Where X_{C-A} , X_{C-B} , X_{C-C} , and X_{C-D} represent horizontal coordinates of centres of mass for fuzzy sets: Highly Acceptable Project, Very Acceptable Project, Acceptable Project, and Low Acceptable Project, respectively.

CASE STUDY

Exactly 25 boiler rooms in 6 Serbian cities (Belgrade-BG, Niš-NI, Užice-UE, Valjevo-VA, Novi Pazar-NP, and Smederevo-SM) that are sources of significant pollution are considered. In Appendix [Table A1](#), the list of boiler rooms is presented together with their basic technical and operational characteristics: total heat power [MW], fuel type, average annual fuel consumption [t], consumer, and heated space [m²].

The total capacity of 25 boiler rooms is 241.7 MW. The average annual consumption of these boiler rooms is 13,450.2 t of heavy fuel oil, 2,567 t of coal, and 452.66 t of heating oil. In total, these boiler rooms provide heat for over 990,000 m² of residential, public (schools, kindergartens, hospitals, etc.), and commercial buildings.

Using these data, indicators of energy efficiency and GHG and pollutant emissions are calculated. In addition, the costs of energy production related only to fuel used are calculated. The obtained data are presented in Appendix [Table A2](#).

An overview of the presented data reveals significant differences in energy efficiency. The average relative consumption of heat is 121.3 kWh/m² or 0.053 kWh/m²/HDD, with the ratio between the minimal and maximal values of 1:8 in the first case and 1:10 in the second. This situation indicates that, in boiler room decommissioning projects, energy efficiency measures should be implemented on the consumption side. Concerning emissions, these facilities, located mainly in the downtown areas, currently emit 47,392.67 t of CO₂eq, 65 t of NO_x, 58 t of SO₂, 3.2 t of CO, and 6.1 t of PM annually. The average operation cost of thermal energy production is 0.093 EUR/kWh.

Each of the considered boiler rooms is a unique case in terms of the availability of the district heating network for connection, and the renewable energy source that can be used.

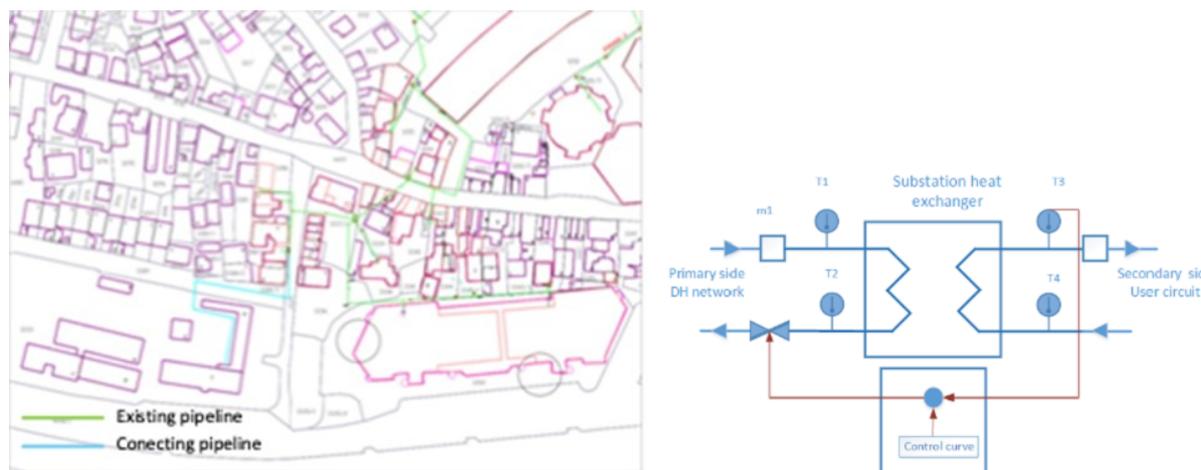


Figure 2. Layout of existing DH network, connecting pipeline, and schematic of heat substation

As an example, the typical case of connection to an existing DH network is presented in [Figure 2](#) (the case NP2: 2,711 m² large public buildings currently heated by a 0.6 MW heating oil boiler). [Figure 2](#) presents the layout of the existing DH network, along with the route of the connecting pipeline to be built from the connection point to the existing DH network to the location of the existing boiler room, where it is envisaged that the DH substation will be installed. The presented heat substation enables the integration of existing consumers into the district heating system.

Connection to the DH network reduced heating costs from 0.074 EUR/kWh to 0.056 EUR/kWh, and the simple payback of investments (in pipelines and heating substation) is 5.3 years. Annual emissions reductions due to the decommissioning of this boiler house are 64.1 t CO₂eq, 41.6 kg NO_x, 12.4 kg SO₂, 1.2 kg CO, and 0.75 kg PM. Calculated Relative Emission Reduction and Costs of Emission Reduction are 112 kg/kW and 1,063 EUR/t, respectively.

The second type of project is related to the substitution of harmful boiler houses with a new RES-based heat source. The general case of substitution is presented in **Figure 3**. RES-based (biomass, solar thermal, or ambient heat via heat pump) heat source is used for base load, while the natural gas boiler is used, if necessary, as a secondary energy source for peak load. Heat accumulator (storage) is an option to improve system feasibility, especially when RES is intermittently available (e.g., solar energy).

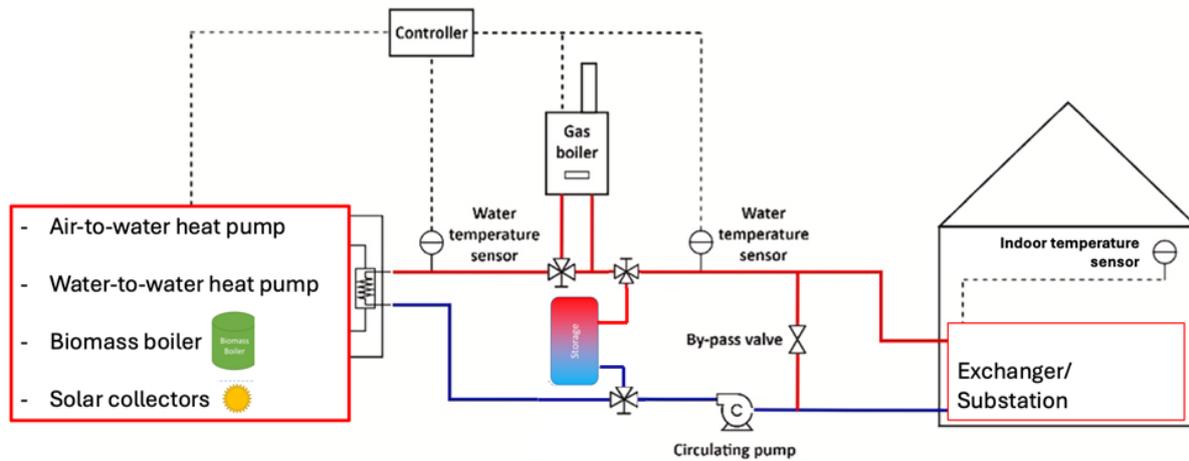


Figure 3. General scheme of RES utilisation for boiler house decommissioning

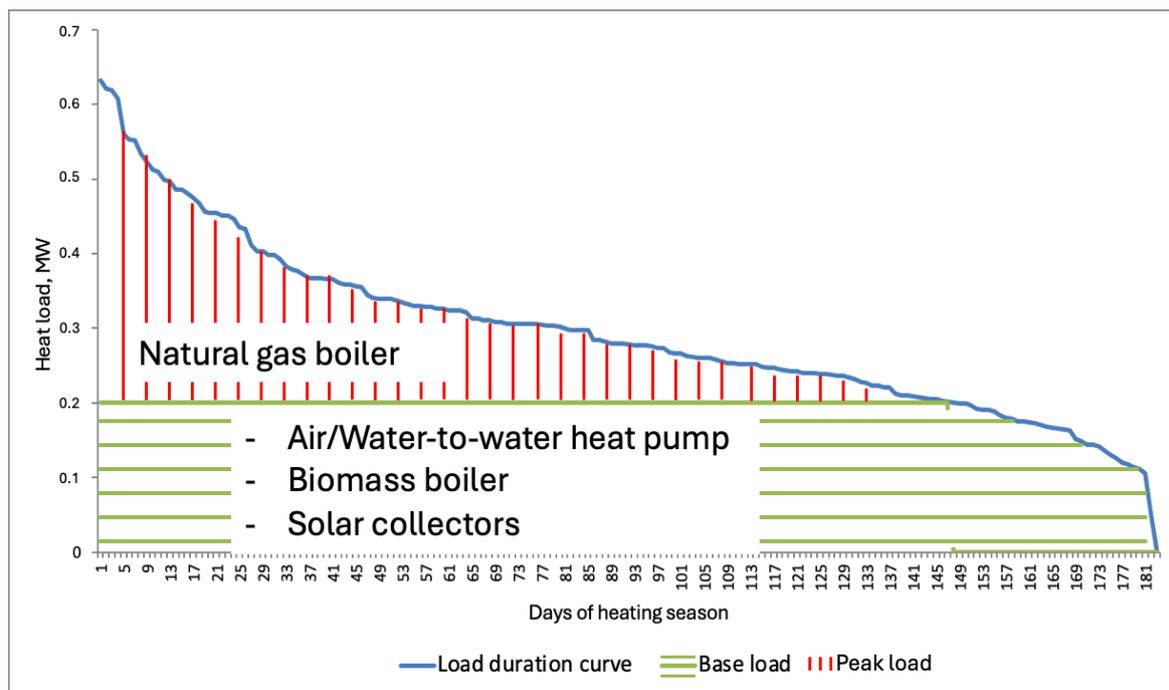


Figure 4. Load duration curve

For each case, a heat load duration curve is created (**Figure 4**). The area under the curve represents the yearly heat demand. It is used to select the optimal heat power for the base-load device and the peak boilers. As with the DH network connection, a simple payback period is calculated using investment costs and the difference in the costs of produced heat before and after boiler room decommissioning. Emission reduction is calculated using emission factors.

Solutions for decommissioning each of the boiler houses are presented in **Table 2**, together with calculated values of indicators (based on data presented in Appendix **Table A3** and **Table A4**).

Table 2. Project Solutions and Indicators of project feasibility and environmental efficiency

Project code	Project solutions	Payback period [year]	Relative emission reduction [kg/kW]	Costs of emission reduction [EUR/t]
BG 1	Air-Water HP (2 × 250 kW + 200 kW) NG boiler (3.6 MW)	9.4	1,156	374
BG2	Connection to DH system	2.6	1,488	69
BG3	Connection to DH system	54.3	574	871
BG4	Connection to DH system	2.2	141	1,112
BG7	Air source HP (2 × 0.6 MW) NG boiler (6MW)	9	249	876
BG9	Connection to DH system	14.6	714	752
BG10	Air source HP 200 + 300 kW, NG boilers (2 × 2 MW)	8	981	229
BG11	Connection to DH system	2	192	661
BG12	Connection to DH system	2.7	79	3,407
BG13	Hybrid solar-gas heating system - solar thermal collectors	2.6	48	2,096
BG14	Air source HP 150 kW	30.9	144	7,176
SM1	Waste heat from ironworks	9	1,216	654
VA1	Air source HP 400 kW, PV plant 150kW	13.4	682	1,067
VA2	Connection to DH system	9.2	711	1,408
UE1	Connection to DH system	8	201	1,964
UE2	Water source HP 3 MW, NG boilers (2 × 7 MW)	6.6	4167	312
NP1	Pellet boiler (0.15 MW) NG boiler (0.45 MW)	11.7	955	244
NP2	Connection to DH system	5.3	112	1,063
NP3	Pellet boiler (2 × 0.6 MW)	21.1	254	1,182
NP4	Air source HP (0.15 MW) NG boiler (0.5 MW)	33.9	545	834
NI1	Woodchips boiler (2 MW) NG boiler (4 MW)	26.1	264	1,602
NI2	Pellet boiler (0.25 MW) NG boiler (0.75 MW)	8.7	611	534
NI3	Woodchips boiler (1 MW) NG boiler (3 MW)	13.3	242	2,700
NI4	Wood residues boiler (1 MW)	159	196	3,330
NI5	Air source HP (40 kW) NG boiler (150 kW)	12.1	194	9,295

For 9 of the boiler houses, the solution is the connection to DH networks. A combination of air-to-water heat pumps (HPs) and natural gas (NG) boilers is proposed for 6 cases, with an additional HP as a stand-alone solution.

Biomass-based solutions (wood chips, pellets, wooden residues) are considered in 6 cases. The solution proposed for decommissioning several boiler rooms in Smederevo (SM1) is the construction of an 11 km long heating pipeline from nearby ironworks, supplying local heating substations to be installed at the locations of the existing boiler rooms. The other RES-based solutions include one water-to-water heat pump and one hybrid solar-gas heating system. Proposed project solutions provided 55% reductions in GHG (CO₂eq) emissions, 88% reductions in NO_x emissions, 99% reductions in SO₂ emissions, 74% reductions in CO emissions, and 93% reductions in PM emissions.

The traditional approach in project selection is based on the payback period. Projects with the shortest payback would have priority in realisation. However, a more detailed investigation of **Table 2** shows that some very feasible projects have a relatively modest impact on emission reduction (BG12) and relatively high costs of relative emission reduction (BG12, BG13). On the other hand, some projects with very long payback periods are highly favourable from an environmental perspective (BG14, NI3, NI4, etc.). The proposed FDM model addresses this problem by assigning equal significance to all indicators in the ranking process.

In addition, the overview of indicator values shows a very wide range of values. A simple payback period is in the range from 2 years to more than 50 years! The relative emission reduction in the most efficient case exceeds 4000 kg/kW, but for some solutions, it is less than 100 kg per kW of installed new capacity. Similarly, the cost of reducing pollutant emissions ranges from a very low 69 EUR/t to an incredibly high 9,295 EUR/t. This great variety of indicator values is the consequence of local specificities, which should be examined in detail in further phases of the project's development. However, for project comparison and ranking, the FDM model is shown to be suitable for handling these wide ranges. Indicators are grouped into sets described by linguistic description/linguistic variables of fuzzy sets – see **Figure 1**. In the same Figure, very simple linear mapping rules between indicators and class j are presented by two parallel horizontal axes.

The FDM model implementation for evaluating two project solutions (NP2 and NP3) is presented as an example. The NP2 project involves boiler room decommissioning via connection to the local DH network, while the NP3 project involves boiler room decommissioning by installing a new pellet boiler. The FDM procedure is presented briefly in **Table 3**. The graphical interpretation of the input fuzzy sets and project assessments for these two cases is presented in **Figure 5** and **Figure 6**.

Table 3. Assessments of project solutions for NP2 and NP3 boiler rooms by using FDM

	NP2	NP3
Input data	Simple Payback 5.3 years Relative Emission Reduction 112 kg/kW Costs of Emission Reduction 1,063 EUR/t	Simple Payback 21.1 years Relative Emission Reduction 254 kg/kW Costs of Reduction 1,182 EUR/t
Fuzzy sets	<i>SP</i> – 1 × profitable <i>RE</i> – 1 × moderate reduction <i>CR</i> – 0.7 × moderately expensive reduction 0.3 × expensive reduction	<i>SP</i> – 1 × unprofitable <i>RE</i> – 1 × moderate reduction <i>CR</i> – 0.1 × moderately expensive reduction 0.9 × expensive reduction
PA, Project Assessment	21% (highly acceptable) 24% (very acceptable project) 27% (acceptable project) 29% (low acceptable project)	19% (highly acceptable) 18% (very acceptable project) 35% (acceptable project) 29% (low acceptable project)
Z(PA)	5.86	6.26

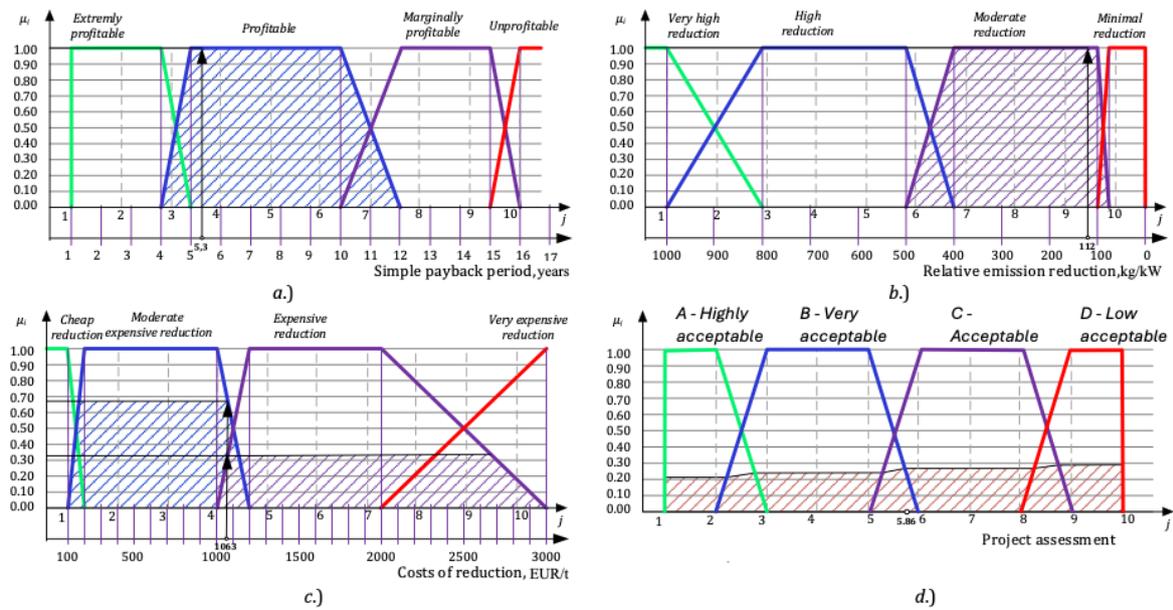


Figure 5. Indicators' fuzzy sets and project assessment for NP2 boiler room

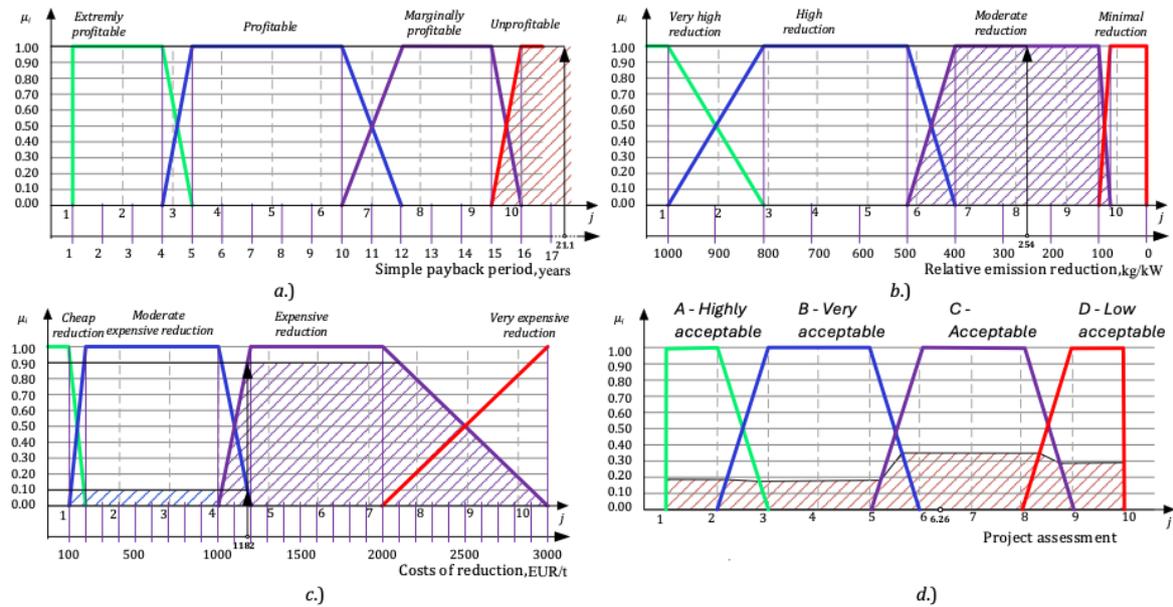


Figure 6. Indicators' fuzzy sets and project assessment for NP3 boiler room

Comparing the "Project assessment" fuzzy sets for these two project solutions, it is clear that NP2 decommissioning remains the preferable project, as the initial simple payback periods comparison shows. However, the differences between the solutions are not so extreme. The "centre of mass" for NP2 has a lower value (5.86) and belongs to the "Very Acceptable" and "Acceptable" fuzzy sets, while the dominant fuzzy set in the fuzzy number of project assessment for NP3 is "Acceptable". In this way, all aspects of interest, both financial and environmental, are considered.

With regard to the prioritisation results for all projects, the list of projects, presented per their acceptability (from the highest to the lowest), is shown in Table 4. Just one project for a harmful boiler decommissioning can be characterised as "Highly Acceptable", while most of the 17 projects belong to the "Very Acceptable" fuzzy set. The "Acceptable" fuzzy set is dominant for 7 solutions. This result means that including the environmental benefits of considered projects in their evaluation improved their attractiveness for implementation.

Table 4. Ranking of projects per the FDM model

Project code	Dominant fuzzy set	Project Score
BG2	Highly Acceptable	1.00
BG11		4.00
BG 1		5.02
SM1		5.02
UE2		5.02
BG10		5.04
NI2		5.04
NP1		5,04
BG4		5.11
BG9		Very Acceptable
BG7	5.50	
VA2	5.51	
BG3	5.65	
NP4	5.65	
VA1	5.74	
BG13	5.86	
UE1	5.86	
NP2	5.86	
NI5	6.04	
NI3	6.06	
NP3	6.26	
NI1	Acceptable	6.28
BG14		6.54
NI4		6.54
BG12		7.00

DISCUSSION

The fuzzy sets shown in [Figure 1](#) were derived from the authors' subjective expert assessment. From the perspective of the results' sensitivity, projects located at the borders between the two linguistic variables are critical. [Table 5](#) presents seven projects whose indicators are located within the overlapping regions of two linguistic descriptions. To examine the model's robustness to fuzzy-set threshold selection, a scenario was considered in which the fuzzy set boundaries were shifted so that the indicators fell within a single fuzzy set. As project NP1 contains two indicators positioned within overlapping regions of linguistic variables, a total of 16 different cases were examined. The results show that a change in membership to the dominant fuzzy set occurred in only two cases (projects NP2 and VA1, where, if the *CR* indicator is classified solely as "Moderately Expensive", the projects become "Very Acceptable"). This situation indicates that the boundaries of the linguistic variables were selected so that the final project assessment would not change significantly when the thresholds are modified.

It should also be emphasised that the purpose of the proposed model is not to provide strict project rankings, but rather to prioritise projects for the subsequent project development process. Therefore, the sensitivity analysis was intentionally focused on the model's robustness to the definition of linguistic variables, as these thresholds are the primary source of subjectivity in early-stage fuzzy decision-making models. Sensitivity to input data uncertainty was not explicitly analysed, as the aim was to assess stability with respect to expert interpretation rather than measurement variability.

Table 5. Effects of the fuzzy sets' thresholds changing to membership of PA fuzzy sets

Project	Indicator	Project Assessment	Changing in fuzzy sets	
NP1	SP: Profitable /Marginally Profitable	Very acceptable	SP: Profitable PA: Very acceptable	SP: Marginally profitable PA: Very acceptable
	RE: Very high reduction/ High reduction	Very acceptable	RE: Very high reduction PA: Very Acceptable	RE: High reduction PA: Very acceptable
NP2	CR: Moderately expensive/ Expensive	Acceptable	CR: Moderately expensive PA: Very acceptable	CR: Expensive PA: Acceptable
NP3	CR: Moderately expensive/ Expensive	Acceptable	CR: Moderately expensive PA: Acceptable	CR: Expensive PA: Acceptable
VA1	CR: Moderately expensive/ Expensive	Acceptable	CR: Moderately expensive PA: Very acceptable	CR: Expensive PA: Acceptable
BG4	CR: Moderately expensive/ Expensive	Very acceptable	CR: Moderately expensive PA: Very acceptable	CR: Expensive PA: Very acceptable
BG13	CR: Expensive/ Very expensive	Acceptable	CR: Expensive PA: Acceptable	CR: Very expensive PA: Acceptable
NI3	CR: Expensive/ Very expensive	Acceptable	CR: Expensive PA: Acceptable	CR: Very expensive PA: Acceptable

The proposed method is intended for use in the early stages of project development, when the available data on project solutions are relatively limited, and when all project indicators – financial profitability, emission reduction potential, and emission reduction costs – are considered with equal importance. The equal importance of indicators is consistent with screening-level decision-making frameworks, where the objective is not optimisation, but identification of broadly preferable alternatives for further detailed analysis. **Table 6** presents the ranking of projects (top five) obtained both based on individual indicators and using the FDM method. It is evident that the “best projects” according to the FDM approach are also prioritised when evaluated against individual indicators, while the only project classified as "Highly Acceptable" (B2) ranks among the top priorities for each of the three considered indicators. The results clearly demonstrate a significant deviation from conventional project evaluation approaches that focus exclusively on financial aspects.

The last column of **Table 6** presents the ranking of projects (top five) obtained based on the sum of normalised indicator values – scoring model; to ensure a fair comparison with the FDM method, equal importance was assigned to each indicator. The results are broadly consistent, with three identical projects appearing in both groups, though in slightly different order. At the

same time, the findings indicate that the FDM model is less sensitive to extreme values of individual project indicators.

Table 6. Projects ranking by different criteria and methods

Shortest <i>SP</i>	Highest <i>RE</i>	Ranking by		
		Lowest <i>CR</i>	FDM	Scoring model
BG11	UE2	BG2	BG2	BG2
BG4	BG2	BG10	BG11	UE2
BG2	SM1	NP1	BG 1	BG10
BG13	BG1	BG8	SM1	BG1
BG12	BG10	UE2	UE2	NP1

The FDM method can be particularly useful in the initial stages of project assessment, when available data are relatively uncertain and conclusions based solely on their absolute values – especially in the presence of extreme values – may lead to misleading interpretations. These findings further support the premise that the fuzzy approach is especially beneficial when the available data are highly uncertain. This confirms that the FDM approach provides comparable results while offering greater robustness against extreme indicator values.

The method is easily transferable to other cases, not only in Serbia but universally. The proposed algorithm for analysing and ranking solutions remains the same. Of course, local context (e.g., costs of proposed facilities, fuel emission factors, district heating fuel mix, etc.) should be taken into account in the calculation. However, the most important change is in the determination of thresholds for linguistic variables. They should be carefully adapted in accordance with the values of the indicators obtained for the projects under consideration. The result cannot be specified in advance; it is determined only after indicators are calculated and grouped by value. The expert's judgment is then crucial in determining the linguistic variable limits to clearly separate them.

CONCLUSIONS

Environmental reasons make it urgent to decommission environmentally harmful and obsolete boiler rooms located in densely populated urban areas. These boiler rooms use coal and liquid fossil fuels (heavy fuel oil, heating oil). Given the need to decarbonise the heating sector soon, as well as potential supply issues, the simple fuel switch of these boiler rooms to natural gas cannot be accepted as a desirable option.

Therefore, this paper proposes a simple procedure for decommissioning harmful boiler rooms by replacing them with district heating systems or local heat sources powered by renewable sources. Although district heating systems are currently mostly fossil-fueled, their local emissions are better regulated and specifically lower. In addition, district heating systems are planned for decarbonisation and are expected to develop towards the 4th and 5th generations. This situation implies greater reliance on renewables and waste heat as energy sources.

The procedure outlined in this paper specifically focuses on its implementation in 25 boiler rooms across six Serbian cities. The effects of these projects' realisation would be a 55% reduction in GHG (CO₂eq) emissions, an 88% reduction in NO_x emissions, a 99% reduction in SO₂ emissions, a 74% reduction in CO emissions, and a 93% reduction in PM emissions compared to the present state. However, the financial and environmental indicators for projects are quite different and somewhat difficult to use for project prioritisation.

The Fuzzy Decision-Making model is proposed for ranking projects based on an overall score that comprises three indicators: simple payback period, relative emission reduction, and

the cost of emission reduction. Starting from the universal principles for the selection and weighting of decision criteria – namely, systemic, consistency, independence, measurability, and comparability – the proposed methodology satisfies all these requirements. It is consistent with the decision objectives of meeting energy demand while reducing emissions, systemic in providing a comprehensive multi-criteria evaluation that yields more robust results than single-criterion assessments, and uses independent and measurable criteria that do not overlap and can be expressed in quantitative terms. Financial and environmental indicators are defined with four linguistic variables each, represented as fuzzy relations based on empirical and expert knowledge. The synthesis of fuzzy relations is performed using max-min fuzzy composition, yielding the project score. The obtained results show that most of the 17 project solutions belong to the "Very Acceptable" fuzzy set. Just one project has even better characteristics and belongs to the "Highly Acceptable" fuzzy set, while seven project solutions are evaluated as "Acceptable" only.

The proposed methodology for project solution evaluation was shown to be very suitable for boiler decommissioning projects, as it considers both environmental benefits and financial parameters of project implementation, helping decision-makers prioritise project realisation. The methodology is transferable to other cases with thresholds for linguistic variables, by taking into account the provided local conditions. Moreover, if the proposed procedure for defining project solutions and the methodology for their evaluation are treated as a single integrated process, feedback from the project evaluation can be used to optimise the project solutions in subsequent phases of project development.

ACKNOWLEDGMENTS

The authors are grateful to the European Bank for Reconstruction and Development (EBRD) for allowing the use of the results of the Scoping Study "Air Quality Improvement Project in Serbia – The Decommissioning of Environmentally Harmful Boiler Rooms in Cities," funded by Renewable District Energy in the Western Balkans Program of the Austrian Government.

The authors acknowledge the support of the Science Fund of the Republic of Serbia, Grant No. 4344, "Forward-Looking Framework for Accelerating Households" Green Energy Transition – FF GreEN.

NOMENCLATURE

Symbols

<i>CR</i>	Costs of emission reduction
<i>FN</i>	Fuzzy number
<i>PA</i>	Project assessment
<i>RE</i>	Relative emission reduction
<i>SP</i>	Simple payback period
<i>Z</i>	Project score

Greek letters

μ	Membership function value (degree of membership)
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Subscripts and superscripts

<i>j</i>	Class/category of the measurement unit
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Abbreviations

BG	Belgrade
CH ₄	Methane

CO	Carbon monoxide
CO ₂	Carbon dioxide
CO ₂ eq	Carbon dioxide equivalent
DH	District heating
FDM	Fuzzy Decision-Making
FS	Fuzzy sets
GHG	Greenhouse gases
HDD	Heating Degree Day
HP	Heat pump
LV	Linguistic variable
NG	Natural gas
NO _x	Nitrogen oxides
N ₂ O	Nitrous oxide
NP	Novi Pazar
PM	Particulate matter
RES	Renewable energy source
SM	Smederevo
SO ₂	Sulphur dioxide
UE	Užice
VA	Valjevo

REFERENCES

1. European Environment Agency, Air Quality in Europe – 2022 Report, <https://www.eea.europa.eu/en/analysis/publications/air-quality-in-europe-2022>, [Accessed: Feb. 02, 2026].
2. International Energy Agency (IEA), Net Zero by 2050: A Roadmap for the Global Energy Sector - 2021, https://iea.blob.core.windows.net/assets/deebef5d-0c34-4539-9d0c-10b13d840027/NetZeroBy2050-ARoadmapfortheGlobalEnergySector_CORR.pdf, [Accessed: Feb. 02, 2026].
3. Ivanovic, V., Tombarevic, E., Šekularac, M., In situ measurements of pollutants emissions from individual coal and briquette-fired furnaces in Pljevlja, *SIMTERM 2019 - 19th International Conference on Thermal Science and Engineering of Serbia*, Sokobanja, Serbia, October 22-25, 2019.
4. Madjar, A., Gjorshoska, I., Prodanova, J., Dedinec, A., Kocarev, L., Western Balkan societies' awareness of air pollution. Estimations using natural language processing techniques, *Ecological Informatics*, Vol. 75, 102097, 2023, <https://doi.org/10.1016/j.ecoinf.2023.102097>.
5. Fallahpour, A., Wong, K. Y., Rajoo, S., Olugu, E. U., Nilashi, M., Turskis, Z., A Fuzzy Decision Support System for Sustainable Construction Project Selection: An Integrated FPP-FIS Model, *Journal of Civil Engineering and Management*, Vol. 26, No. 3, pp 247–258, 2020, <https://doi.org/10.3846/jcem.2020.12183>.
6. Mikulandrić, R., Krajačić, G., Duić, N., Khavin, G., Lund, H., Vad Mathiesen, B., Østergaard, P., Performance Analysis of a Hybrid District Heating System: A Case Study of a Small Town in Croatia, *J. Sustain. Dev. Energy Water Environ. Syst.*, Vol. 3, No. 3, pp 282–302, 2015, <https://doi.org/10.13044/j.sdewes.2015.03.0022>.
7. Pereira, C., Miguez, M., Di Gregorio, L., Haddad, A., Verol, A., Inundation Risk Index as an Urban Planning Supportive Tool, *J. Sustain. Dev. Energy Water Environ. Syst.*, Vol. 8, No. 2, pp 235-251, 2020, <https://doi.org/10.13044/j.sdewes.d7.0288>.
8. Fedakar, H. I., Dinçer, A. E., Demir, A., Comparative analysis of hybrid geothermal-solar systems and solar PV with battery storage: Site suitability, emissions, and economic performance, *Geothermics*, Vol. 125, 103175, 2025, <https://doi.org/10.1016/j.geothermics.2024.103175>.

9. Liyanage, D. R., Hewage, K., Karunathilake, H., Sadiq, R., Feasibility of carbon-capturing in building heating systems: A life cycle thinking-based approach, *International Journal of Greenhouse Gas Control*, Vol. 132, 104056, 2024, <https://doi.org/10.1016/j.ijggc.2023.104056>.
10. Alemam, A., Al-Widyan, M., Technical, economic, and environmental assessment of integrating solar thermal systems in existing district heating systems under Jordanian climatic conditions, *J. Sustain. Dev. Energy Water Environ. Syst.*, Vol. 10, No. 3, 1090395, 2022, <https://doi.org/10.13044/j.sdewes.d9.0395>
11. Wang, J., Jing, Y., Zhang, C., Zhao, J., Review on multi-criteria decision analysis aid in sustainable energy decision-making, *Renewable and Sustainable Energy Reviews*, Vol. 13 No. 9, pp 2263-2278, 2009, <https://doi.org/10.1016/j.rser.2009.06.021>.
12. Vasić, G., Application of multi criteria analysis in the design of energy policy: Space and water heating in households – City Novi Sad, Serbia, *Energy Policy*, Vol. 113, pp 410-419, 2018, <https://doi.org/10.1016/j.enpol.2017.11.025>.
13. Bozhikaliev, V., Sazdovski, I., Adler, J., Markovska, N., Techno-economic, Social and Environmental Assessment of Biomass Based District Heating in a Bioenergy Village, *J. Sustain. Dev. Energy Water Environ. Syst.*, Vol. 7, No. 4, pp 601-614, 2019, <https://www.sdewes.org/jsdewes/pid7.0257>.
14. Alyamani, R., Long, S., The Application of Fuzzy Analytic Hierarchy Process in Sustainable Project Selection, *Sustainability*, Vol. 12, No. 20, 8314, 2020, <https://doi.org/10.3390/su12208314>.
15. Ddiba, D., Andersson, K., Dickin, S., Ekener, E., Finnveden, G., A review of how decision support tools address resource recovery in sanitation systems, *Journal of Environmental Management*, Vol. 342, 118365, 2023, <https://doi.org/10.1016/j.jenvman.2023.118365>.
16. Tanasijevic, M., Jovancic, P., Ivezic, D., Bugarcic, U., Djuric, R., A Fuzzy-Based Decision Support Model for Effectiveness Evaluation – A Case Study of Examination of Bulldozers, *International Journal of Industrial Engineering: Theory, Applications and Practice*, Vol. 26, No. 6, pp 878–897, 2019, <https://doi.org/10.23055/ijietap.2019.26.6.3304>.
17. Ross, T. J., *Fuzzy Logic with Engineering Applications*, John Wiley & Sons Ltd, 2010, <https://doi.org/10.1002/9781119994374>.
18. Oyatoye, E. O., Balogun, D. A., Adebisi, S. O., Oyenuga, O. G., Fuzzy Multi-Criteria Decision-Making Model for Prioritization of Road Project Investments: Validity Evidence from Lagos State, *Kelaniya Journal of Management*, Vol. 12, No. 1, pp 90–116, 2023, <https://doi.org/10.4038/kjm.v12i1.7732>.
19. Tamtam, F., Amzil, M., Jenkal, W., Tourabi, A., Artificial Intelligence-Supported Hyperfuzzy Framework for Sustainable Supply Chain and Energy Optimization in Smart Cities, *J. Sustain. Dev. Energy Water Environ. Syst.*, Vol. 13, No. 4, 1130620, 2025, <https://doi.org/10.13044/j.sdewes.d13.0620>.
20. Ivezić, D., Živković, M., Madžarević, A., Pavićević, V., Stojanović, D., Scoping Study “Air Quality Improvement Project in Serbia – The Decommissioning of Environmentally Harmful Boiler Rooms in Cities”, EBRD, Belgrade, 2024.
21. Ghafghazi, S., Sowlati, T., Shahab, S., Melin, S., Techno-economic analysis of renewable energy source options for a district heating project, *International Journal of Energy Research*, Vol. 34, No. 12, pp 1109–1120, 2010, <https://doi.org/10.1002/er.1637>.
22. Pursiheimo, E., Rämä, M., Optimal Capacities of Distributed Renewable Heat Supply in a Residential Area Connected to District Heating, *J. Sustain. Dev. Energy Water Environ. Syst.*, Vol. 9, No. 1, 1080328, 2021, <https://doi.org/10.13044/j.sdewes.d8.0328>.

23. Gómez, D. R., Watterson, J. D., Americano, B. B., Ha, C., Marland, G., Matsika, E., Namayanga, L. N., Osman-Elasha, B., Saka, J. D. K., Treanton, K., Chapter 2: Stationary Combustion, in: 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K., eds., IGES, Japan, 2006.
24. Juhrich, K., Beckers, R., Updating the Emission Factors for Large Combustion Plants, TEXTE 141/2019, German Environment Agency (UBA), Dessau-Roßlau, 2019.
25. Gudmundsson, O., Thorsen, J. E., Zhang, L., Cost analysis of district heating compared to its competing technologies, *WIT Transactions on Ecology and the Environment*, Vol. 176, pp 3-13, 2013, <https://doi.org/10.2495/esus130091>.
26. Martínez-Ruiz, Y., Manotas-Duque, D. F., Ramírez-Malule, H., Financial risk assessment of a district cooling system, *Energy*, Vol. 278, Part A, 127879, 2023, <https://doi.org/10.1016/j.energy.2023.127879>.
27. Trading Economics, EU Carbon Permits, <https://tradingeconomics.com/commodity/carbon>, [Accessed: Nov. 15, 2025].
28. European Environment Agency, Greenhouse gas emission intensity of electricity generation in Europe, <https://www.eea.europa.eu/en/analysis/indicators/greenhouse-gas-emission-intensity-of-1>, [Accessed: Nov. 15, 2025].
29. OECD, Effective Carbon Rates 2021, https://www.oecd.org/en/publications/effective-carbon-rates-2021_0e8e24f5-en.html, [Accessed: Nov. 15, 2025].
30. Gilling, Joseph, G., Johnson, I., Wolman, P., Economic Costs of carbon dioxide reduction strategies, Global Environment Facility (GEF) working paper no. 3, World Bank, Washington, D.C., USA, 1992.
31. Belton, V., Stewart, T. J., *Multiple Criteria Decision Analysis: An Integrated Approach*, Springer New York, NY, 2002, <https://doi.org/10.1007/978-1-4615-1495-4>.
32. Zadeh, L. A., Fuzzy sets, *Information and Control*, Vol. 8, No. 3, pp 338–353. [https://doi.org/10.1016/S0019-9958\(65\)90241-X](https://doi.org/10.1016/S0019-9958(65)90241-X).
33. Zimmermann, H.-J., *Fuzzy Set Theory and Its Applications*, Springer Science+Business Media, New York, 2001, <https://doi.org/10.1007/978-94-010-0646-0>.
34. Bien, Z., Min, K. C., *Fuzzy Logic and its Applications to Engineering, Information Sciences, and Intelligent Systems*, Springer Dordrecht, 1995, <https://doi.org/10.1007/978-94-009-0125-4>.
35. Ojha, V., Abraham, A., Snasel, V., Heuristic Design of Fuzzy Inference Systems: A Review of Three Decades of Research, *Engineering Applications of Artificial Intelligence*, Vol. 85, pp 845–864, 2019, <https://doi.org/10.1016/j.engappai.2019.08.010>.
36. Gowrishankar, C., Dharshinee, R., Geetha, K., Properties of Composition of Fuzzy Relations and its Verifications, *International Journal of Management and Humanities*, Vol. 4, No. 5, 2020, <https://doi.org/10.35940/ijmh.E0514.014520>.
37. Wang, J., Yang, J. B., Sen, P., Safety analysis and synthesis using fuzzy set modeling and evidential reasoning, *Reliability Engineering & System Safety*, Vol. 47, No. 3, pp 103–118, 1995, [https://doi.org/10.1016/0951-8320\(94\)00053-Q](https://doi.org/10.1016/0951-8320(94)00053-Q).

APPENDIX

Table A1. Basic technical and operational characteristics of boiler rooms

Boiler room code	Total heat power [MW]	Fuel	Average annual fuel consumption [t]	Consumers	Heated space [m ²]
G1	9.65	Heavy fuel oil	376.63	Admin. buildings	26,576
BG2	40	Heavy fuel oil	1,706.00	Residential & commercial buildings	92,000
BG3	15	Heavy fuel oil	208.30	Admin. buildings	42,000
BG4	10.47	Heating oil	84.88	Admin. buildings	17,600
BG7	7	Coal	2,224.00	Residential and commercial buildings	57,409
BG9	11.63	Heavy fuel oil	618.00	Admin. buildings	44,261
BG10	4.3	Heavy fuel oil	273.80	Admin. buildings	n/a
BG11	0.62	Heating oil	23.76	Kindergarten	2,296
BG12	2	Heating oil	75.00	School	7,235
BG13	1.8	Heating oil	61.93	School	7,114
BG14	0.15	Heavy fuel oil	9.49	Museum	1,146
	43	Heavy fuel oil	3,801.00	Admin. building	31,815.5
	8	Heavy fuel oil	331.07	Residential and commercial buildings	23,879
	6.86		347.93		33,061
	6.98		436.86		27,257
SM1	5.58	Heavy fuel oil	315.87	Residential and commercial buildings	21,819
	2.56		212.75		9,105
	4.65		259.40		22,119
	6.95	Heavy fuel oil	482.53	Residential and commercial buildings	34,208
VA1	0.8	Heavy fuel oil	30.00	School	3,550
VA2	0.35	Heating oil	24.16	Kindergarten	1,069
UE1	0.12	Heating oil	11.50	Admin. buildings	750
UE2	14	Heavy fuel oil	2,227.00	Residential and commercial buildings	11,891.1
NP1	2.2	Coal	242.67	Residential and commercial buildings	5,337
NP2	0.6	Heating oil	21.00	Public buildings	2,711
NP3/NP4	1	Coal/Firewood	100.00	School	4,350
NI1	6.978	Heavy fuel oil	233.66	Residential and commercial buildings	15,842
NI2	1.5	Heavy fuel oil	80.66	Residential and commercial buildings	6,991
	1.22	Heating oil	38.82		10,299
NI3	3.012	Heavy fuel oil	151.00	Residential and commercial buildings,	12,623
	3	Heating oil	51.60	School, Kindergarten	4,400
	0.4	Heating oil	17.20		1,500
NI4	0.5	Heavy fuel oil	33.33	Residential buildings	2,836.88
NI5	0.8	Heating oil	20.73	School	2,495

Table A2. Characteristics of boiler room operation □ energy efficiency

Boiler room code	Efficiency of consumption	
	[kWh/m ² /year]	[kWh/m ² /HDD/year]
BG1	163.0	0.081
BG2	139.7	0.073
BG3	45.7	0.023
BG4	45.3	0.023
BG7	120.5	0.060
BG9	130.4	0.066
BG10	285.3	0.113
BG11	96.6	0.048
BG12	97.7	0.039
BG13	70	0.031
BG14	67.13	0.034
	137.40	0.052
	114.7	0.137
	121.0	0.048
SM1	184	0.073
	166.67	0.066
	268.67	0.107
	135	0.054
	106	0.042
VA1	78	0.031
VA2	169	0.068
UE1	143.2	0.055
UE2	125	0.048
NP1	140.3	0.037
NP2	73	0.024
NP3/NP4	102.5	0.033
NI1	134.67	0.052
NI2	105.67	0.0404
	35.67	0.0136
NI3	197.67	0.0756
	102	0.042
	37	0.0139
NI4	107.67	0.041
NI5	78	0.029
Average /Total	121.3	0.053

Table A3. Characteristics of boiler room operation □ emissions and costs

Boiler room code	Annual emissions					Costs of energy production
	[t CO ₂ eq]	[kg NO _x]	[kg SO ₂]	[kg CO]	[kg PM]	[EUR/kWh]
BG1	1,334.3	2,526.0	2,305.0	116.1	230.5	0.079
BG2	5,381.7	10,335.6	9,421.7	478.0	942.7	0.076
BG3	658.7	1,261.9	1150.3	58.4	115.1	0.076
BG4	267.6	168.2	50.0	5.0	3.1	0.152
BG7	2,643.7	1,661.7	494.3	49.8	30.2	0.038
BG9	2,016.0	3.8	3.5	177.0	348.0	0.075
BG10	896.95	1.69	1.55	0.08	0.16	0.075
BG11	74.90	47.10	14.00	1.40	0.857	0.155
BG12	236.4	148.6	44.2	4.5	2.7	0.152
BG13	166.2	104.5	31.1	3.1	1.9	0.178
BG14	25.7	16.2	4.8	0.5	0.3	0.076
	12,338.6	23,138.3	21,092.3	1,070.2	2,110.5	
	1,074.5	2,015.1	1,836.9	93.2	183.8	
	1,129.3	2,117.7	1,930.5	98.0	193.2	
SM1	1,335.1	2,503.7	2,282.3	115.8	228.4	0.093
	1,025.2	1,922.6	1,752.6	88.9	175.4	
	690.5	1294.9	1,180.4	59.9	118.1	
	842	1578.9	1,439.3	73	144	
	1,566.2	2,937	2,677.3	135.8	267.9	
VA1	99.1	182.6	166.5	8.4	16.7	0.061
VA2	65.6	40.8	81.8	4.2	8.2	0.122
UE1	35.39	0.02	0.01	0	0	0.153
UE2	7157.43	13.55	12.35	0.63	1.24	0.081
NP1	259.8	256.9	321.5	57.3	6.1	0.038
NP2	66.2	41.6	12.4	1.2	0.75	0.074
NP3/NP4	153.9	189.2	192.7	41.2	4	0.049
NI1	598	1,132.3	1,032.2	52.4	103.3	0.076
NI2	206.4	390.9	356.3	18.1	35.7	0.077
	98.2	61.7	18.4	1.8	1.1	
NI3	386.4	731.7	667	33.8	66.7	0.11
	130.1	81.8	24.3	2.5	1.5	
	43.4	27.3	8.1	0.8	0.5	
NI4	85.3	161.5	147.2	7.5	14.7	0.076
NI5	52.3	32.9	9.8	1	0.6	0.152
Average /Total	47,284	65,026	57,976	3,226	6,080	0.093

Table A4. Expected costs and emissions reduction for proposed project solutions

Boiler room code	Costs of energy production [EUR/kWh]	Annual emissions reduction				
		[t CO ₂ eq]	[kg NO _x]	[kg SO ₂]	[kg CO]	[kg PM]
BG1	0.044	592.42	2.33	2.30	0.11	0.23
BG2	0.059	2,087.10	8,857.70	9,414.90	395.40	937.90
BG3	0.065	171.40	1,261.90	1,150.30	58.40	115.10
BG4	0.065	74.20	168.20	50.00	5.00	3.10
BG7	0.046	1,914.90	1,267.20	492.50	27.70	28.90
BG9	0.065	1,320.7	3,818.1	3,480.5	176.60	348.30
BG10	0.065	319.00	1.36	1.52	0.06	0.15
BG11	0.069	18.30	47.10	14.00	1.40	0.86
BG12	0.065	55.83	33.81	21.37	-1.81	0.26
BG13	0.037	98.2	67.5	30.9	1.1	1.8
BG14	0.042	6.5	16.2	4.8	0.5	0.3
SM1	0.048	14,133	34,313.2	34,176.9	1,556.2	3,410.7
VA1	0.05	88.6	182.6	166.5	8.4	16.7
VA2	0.063	16.3	14.3	81.7	2.7	8.1
UE1	0.097	11.8	0.02	0.01	0	0
UE2	0.034	1,531.3	6.1	5.6	0.3	0.6
NP1	0.057	218.0	203.9	316.7	47.0	5.6
NP2	0.056	64.1	10.6	1.18	0.61	0.073
NP3	0.046	150.5	52.8	180.4	14.6	2.5
NP4	0.049	83.8	171.8	192.6	40.2	3.9
NI1	0.062	560.1	563.6	982.0	-56.8	97.2
NI2	0.052	158	244.8	343.4	-10.9	34.0
NI3	0.065	560	306.3	667.9	-70.9	63.7
NI4	0.095	82.7	57.4	137.8	-12.8	13.6
NI5	0.044	39.6	26.0	9.7	0.6	0.6
Average/Total	0.058	26.208	57.078	57.497	2.393	5.665



Paper submitted: 25.11.2025
 Paper revised: 10.02.2026
 Paper accepted: 13.02.2026