ANALYSIS AND EVALUATION OF KEY INFLUENCING FACTORS ON THE OPTIMIZATION OF THERMAL ENERGY CONSUMPTION IN INDUSTRIAL THERMAL POWER PLANTS

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In the past, the design and operation of industrial thermal power plants did not give importance to energy consumption. Due to the depletion of fossil fuel reserves and the rising of their prices, restrictions in emission of waste gases into atmosphere, and the need to reduce production costs over the last thirty years, greater attention has been paid to optimizing thermal energy consumption. Various technical, technological, and organizational measures are undertaken to reduce thermal energy consumption. This study examines the proposals for improving the efficiency of thermal energy production in four thermal power plants in Bosnia and Herzegovina. The activities aimed at improving energy efficiency are consolidated and presented through five measures. To determine the optimal measure, the criteria for evaluating each measure are defined. These criteria are analyzed and filtered by using the ISM method, and while the fuzzy AHP method was used for their weights. Finally, the fuzzy TOPSIS method for multi-criteria optimization is applied to select the optimal energy efficiency measure for the analyzed thermal power plants. Additionally, the research defines the order of implementing the selected measures to improve the energy efficiency of the studied thermal power plants.

Key words*: thermal power plants, energy efficiency, ISM, fuzzy AHP, fuzzy TOPSIS*

1. Introduction

Industrial thermal power plants are designed to produce thermal energy by burning various types of fuels. These plants produce steam, which is used in thermal power plants and industrial energy systems to generate electricity and in the chemical, petrochemical, and other industries for the needs of technological processes. Industrial thermal power plants mainly use fossil or nuclear fuels, converting the internal energy of the fuel into electrical or thermal energy through burning in technological processes [1].

Growing awareness of the importance of energy and its rational use, the depletion of reserves, and issues with fossil fuel supplies require comprehensive analyses and the application of new technologies in the production of thermal and electrical energy. Improving the energy efficiency of thermal power plants is one of the most effective ways to reduce thermal energy consumption in industrial processes.

Due to the depletion of fossil fuel reserves, rising prices, restrictions in emission of waste gases, and the drive to reduce production costs, increasing attention has been paid to optimizing thermal energy consumption over the last thirty years. Energy efficiency improvement implies the use of the total thermal energy within the energy system at various available temperature levels to produce useful mechanical work or water steam for technological processes and heating, with minimal dissipation of heat into the environment as waste heat. To reduce thermal energy consumption in industrial thermal power systems, some of the following activities are undertaken: replacement of outdated and energy-inefficient equipment, improvement of the pipeline network for the distribution of thermal energy to consumers, utilization of waste heat through various technical solutions, organizational measures, etc. [2,3].

The state of thermal energy control was analyzed in four thermal power plants in Bosnia and Herzegovina, which use coal as a fuel. The analyses showed numerous technical deficiencies in the production and distribution of thermal energy in these thermal power plants. The optimization of thermal energy consumption was comprehensively considered from the aspects of production, distribution, and consumption. The following methods were used to consider possibilities for improving energy efficiency in the four thermal power plants in Bosnia and Herzegovina: Interpretative Structural Modeling (ISM) for the analysis and filtering of the established criteria, fuzzy AHP method for the evaluation of their weights, and fuzzy TOPSIS method for multi-criteria optimization to determine the optimal energy efficiency measure for the analyzed thermal power plants.

2. Problem statement overview

One of the main goals of modern industrial production is to reduce energy consumption per unit of product. A series of measures and activities in production and power plants can influence the reduction of energy consumption, thereby directly reducing production costs [4]. Investments in increasing energy efficiency are quicker to implement and pay off compared to the building of new energy capacities [5].

Energy efficiency measures in industrial and power plants involve a wide range of activities that influence the reduction of energy consumption, thereby directly impacting production costs [4]. A review of the literature reveals significant efforts to optimize the operation of industrial and power plants, aiming to reduce energy consumption while meeting production requirements. Research shows considerable potential for improving the current situation [6]. Researchers conduct performance analyses of energy production and consumption in industrial thermal power plants [7] and provide guidelines and proposals for improving the sustainable development of electric power systems [2]. Zhang (2020) [1] notes significant energy losses in thermal power plants through boiler losses, pipe losses, mechanical losses, generator losses, etc. Carapellucci and Giordano (2019) [8] state that the efficiency improvement of thermal power plants through heat efficiency improvements can be achieved through one or more processes: increase of the average temperature of heat transfer to the working fluid of steam plants, reduction of the average temperature by dissipating heat from the working fluid in the condenser, improvement of the process flow to reuse the generated waste heat, and the maintenance of the plant component losses at low levels. The same authors believe that the improvement of the net efficiency of thermal power plants should focus on the development of future alternative technologies for fossil fuel use and structural improvements to thermal power plants.

Fuel combustion processes and subsequent heat transfer in boilers can significantly affect the efficiency of the entire thermal power plant [9]. Some activities to improve the energy efficiency of industrial boilers include: more efficient combustion [10,11], heat transfer improvement [12-14], subsequent steam superheating [1,15], use of waste heat [16], etc.

Energy efficiency in thermal power plants should be accompanied by activities and actions that lead to reduced energy consumption. These activities are based on the application of energy-efficient technologies or processes that achieve energy savings and other positive effects. They can include appropriate handling, maintenance, and adjustments, improvement of the efficiency of existing equipment and systems, without changes in any production process of the given plant or in the power supply system [17].

The four thermal power plants in Bosnia and Herzegovina, where the possibility of energy efficiency improvement is considered, were commissioned forty years ago. The energy efficiency of these thermal power plants ranges from 25% to 31%. It is clear that these thermal power plants have relatively low energy efficiency compared to modern thermal power plants, where the efficiency exceeds 41%. In this context, the existing state of thermal energy production and consumption optimization in these thermal power plants was comprehensively analyzed. Based on the conducted research, the following conclusions can be drawn:

- Steam boilers used in the steam production process have up to 20% lower efficiency compared to the latest generation boilers.
- The quality of thermal insulation on certain parts of the pipelines used for steam distribution is unsatisfactory.
- Flange joint seals on the steam distribution network are not optimal.
- Many condensate separators are not functioning.
- The return of condensate and utilization of flash steam is not fully performed.
- A relatively large amount of low-potential waste heat is produced.
- Recorded process data in daily operational reports are mainly archived without analysis.
- There are no procedures for the use of measured process data to analyze and improve operational parameters, especially for boilers as the main elements of power plants.
- Investment in equipment maintenance is insufficient.
- Thermal power plants generally possess and use outdated energy technologies and energy-intensive production technologies.
- Measurement and control equipment is outdated and often not functioning.
- It is not evident that employees (engineers and operators) recognize the importance of activities related to energy efficiency.

Based on the conducted research and the obtained results, it can be concluded that there is ample room for improvement in thermal energy production and consumption optimization in thermal power plants in Bosnia and Herzegovina. A series of individual activities can optimize thermal energy consumption, directly influencing the reduction of electricity production costs. Each individual activity aimed at improving the energy efficiency of thermal power plants contributes to efficiency improvements to a lesser extent than when they are combined. The analyzed measures are based on the improvement of the processes of thermal power plants with or without the replacement of the existing system elements, structural changes (installation of additional components), reconstruction of the distribution network (replacement of thermal insulation, condensate separators, steam headers, etc.), and recuperation of waste heat from working media and flue gases. In this context, individual activities researched through the review of relevant professional literature, insight into technical documentation, and information obtained from experts employed in thermal power plants in Bosnia and Herzegovina have been grouped into five measures (tab. 1).

Table 1. Energy Efficiency Measures for Thermal Power Plants [18]

Number	Measure	Description of Measure
M1	Plant and power grid processes	Improvements made in processes without structural changes, but with increased automation.
M2	Boiler replacement	Replacement of worn-out elements and components that cannot meet nominal requirements.
M3	Burner replacement	Replacement of worn-out elements and components that cannot meet nominal requirements.
M4	Thermotechnical processes	Heat recuperation from all working media.
M5	Pipeline routes	Reduction of heat loss during transport to consumers.

Table 1 shows five grouped measures developed after examining and analyzing technical solutions aimed at optimizing thermal energy consumption in power plants in Bosnia and Herzegovina. These measures primarily affect the optimization of thermal energy consumption and, to some extent, the extension of the lifespan of existing power plants. Also, increasing the capacity i.e. productivity of the power plants was considered, but it was concluded that such an investment would have a relatively long payback period and is not currently justified, and thus this measure was not analyzed.

Although it does not directly affect thermal energy consumption in the reviewed power plants, it would be interesting in future research to analyze measures related to fuel, such as pre-treatment of fuel to improve certain characteristics, substitution of existing fuel with suitable fossil fuel, use of alternative fuels, utilization of waste materials, etc.

3. Research Methodology

The activities aimed at the energy efficiency improvement of thermal power plants are consolidated into five measures: plant and energy network processes, boiler replacement, burner replacement, thermotechnical processes, and pipeline routes.

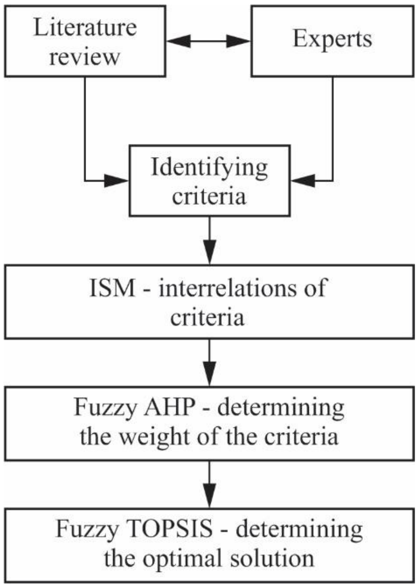

Figure 1. Methodology diagram

Determining the optimal measure is not always simple, especially for complex systems like thermal power plants. In this regard, the criteria used to evaluate energy efficiency measures were analyzed. After defining the criteria by using the ISM (Interpretative Structural Modeling) method, they were analyzed and filtered. After determining the effective criteria, the weights of the criteria were calculated by using the fuzzy AHP (Analytic Hierarchy Process) method and applied to calculate the optimal energy efficiency measure for the thermal power plant by using the fuzzy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method. The methodology diagram is shown in fig. 1

3.1. Defining of criteria

The measures for the energy efficiency improvement of thermal power plants grouped into five measures will not have the same effect, financial outlay, impact on reducing environmental pollution, etc., indicating a multi-criteria problem. Therefore, it is necessary to determine the parameters, or criteria, based on which their effect will be evaluated. A literature review demonstrated that multi-criteria optimization is used in the field of energy efficiency and energy planning. Through literature analysis, gathering information from project documentation, and collaboration with experts from four thermal power plants in Bosnia and Herzegovina, eight criteria were established [18] based on which evaluations and optimal measure calculations can be performed. The established criteria with descriptions are shown in tab. 2.

Table 2. Description of Criteria

Number	Criterion	Description of criterion
C1	Increase in utilization rate	Evaluation of how much the measure contributes to efficiency improvement in percentage.
C2	Reliability and safety in operation	The measure's impact on operational reliability and safety.
C3	Improvement of design solutions	The measure's impact on the improvement of process and equipment management, supervision, and the need for new components.
C4	Investment cost and value	Cost of the investment.
C5	Return on investment	Payback period of the investment.
C6	Environmental impact	The proposed measure's impact on the reduction of emissions to the environment.
C7	Energy cost	The measure's impact on energy cost.
C8	Supply reliability	The measure's impact on the reliability and regularity of supply.

3.2. ISM method – Interpretative Structural Modeling

To understand the interrelationships of the defined criteria and identify the most important among them, the ISM methodology was applied. This method is widely used in various fields such as construction [19], supply chain management [20,21], engineering industry [22-24], and energy supply and efficiency [25-27]. The ISM method can be described through the following steps [28-30]:

- Identify the criteria characteristic for the given problem through literature review and discussions with experts (practitioners and academia). Establish relationships among the criteria and develop the Structural Self-Interaction Matrix (SSIM).
- Form the binary Initial Reachability Matrix (IRM), and, through transitivity checks, determine the Final Reachability Matrix (FRM).
- Partition levels from the FRM into Reachability Set, Antecedent Set, and Intersection Set until all criteria are identified.
- Develop the diagram and conduct the MICMAC analysis.

By using the MICMAC analysis and the ISM diagram, criteria are filtered to be subsequently used in integrated optimization methods (fuzzy AHP and fuzzy TOPSIS).

3.3. Fuzzy AHP

To determine the weight values of the criteria, a fuzzy AHP approach was used, which has been widely applied recently [29,31]. Preference relationships between two criteria are determined by using Hamming distance. If two fuzzy numbers (a and b) are unclear, the preference relationship is [32]:

$$P(a,b) = \frac{D(a,b) + D(a \cap b,0)}{D(a,0) + D(b,0)} \tag{1}$$

Where D(a,b) – a dominates over b; D(a∩b,0) – intersection of a and b; D(a,0) – area of a; and D(b,0) – area of b. The equation shows that preference relations are obtained in related areas [33].

3.4. Fuzzy TOPSIS

The TOPSIS multi-criteria optimization method is based on the concept that the chosen alternative should have the shortest distance from the ideal solution and the longest from the anti-ideal solution [34]. The fuzzy principle in the TOPSIS method aids in finding solutions to problems with unclear decision-makers’ choices for optimal solutions or ranking the alternatives in a fuzzy environment. The procedure can be described through steps that include [29,35]:

- Creating of a decision matrix and forming a normalized decision matrix.
- Forming of a normalized matrix with included weight coefficients.
- Determining of fuzzy ideal solutions and distances of alternatives from fuzzy ideal solutions.
- Determining of the relative closeness of alternatives to the ideal solution and ranking of the alternatives.

4. Optimization of energy efficiency parameters in thermal power plants

4.1. Application of ISM model

The ISM method was applied to eight defined criteria (Table 2). The ISM method reveals interconnections among the criteria. Tab. 3 shows the Structural Self-Interaction Matrix (SSIM) obtained from the evaluations by expert and academic staff.

Table 3. Structural self-interaction matrix

Criteria	C8	C7	C6	C5	C4	C3	C2	C1
C1	O	X	V	V	V	A	O	1
C2	V	X	X	V	V	A	1	
C3	V	V	V	V	V	1		
C4	O	X	A	V	1			
C5	A	A	A	1				
C6	O	V	1					
C7	A	1						
C8	1							

The initial reachability matrix is formed by replacing V, A, X, and O with 1, 0, 1, 0 respectively. After forming the initial matrix, according to ISM rules, to neutralize the gaps in opinions, a transitive final reachability matrix is formed, shown in tab. 4. Transitivity implies that if A is greater than B, and B is greater than C, then A is greater than C. Transitive values are indicated with 1* in tab. 4.

Table 4. Reachability matrix

	C8	C7	C6	C5	C4	C3	C2	C1	Driving
C1	0	1	1	1	1	0	1*	1	6
C2	1	1	1	1	1	0	1	1*	7
C3	1	1	1	1	1	1	1	1	8
C4	0	1	0	1	1	0	1*	1*	5
C5	0	0	0	1	0	0	0	0	1
C6	1*	1	1	1	1	0	1	1*	7
C7	1*	1	1*	1	1	0	1	1	7
C8	1	1	0	1	1*	0	1*	1*	6
Depend	5	7	5	8	7	1	7	7	

After forming the final reachability matrix, iterations resulted in three levels for eight criteria (tab. 5).

Table 5. Levels for each criteria

Criteria	Reachability set	Antecedent set	Intersection	Level
C1	1, 2, 4, 5, 6, 7	1, 2, 3, 4, 6, 7,8	1, 2, 4, 6, 7	**II**
C2	1, 2, 4, 5, 6, 7, 8	1, 2, 3, 4, 6, 7, 8	1, 2, 4, 6, 7, 8	**II**
C3	1, 2, 3, 4, 5, 6, 7, 8	3	3	**III**
C4	1, 2, 4, 5, 7	1, 2, 3, 4, 6, 7, 8	1, 2, 4, 5, 7	**I**
C5	5	1, 2, 3, 4, 5, 6, 7, 8	5	**I**

C6	1, 2, 4, 5, 6, 7, 8	1, 2, 3, 6, 7	1, 2, 6, 7	**II**
C7	1, 2, 4, 5, 6, 7, 8	1, 2, 3, 4, 6, 7, 8	1, 2, 4, 6, 7, 8	**II**
C8	1, 2, 4, 5, 7, 8	2, 3, 6, 7, 8	2, 7, 8	**II**

Based on the levels from tab. 5, fig. 2 shows the obtained ISM graph with indirect connections removed, illustrating the interrelationship of criteria by levels.

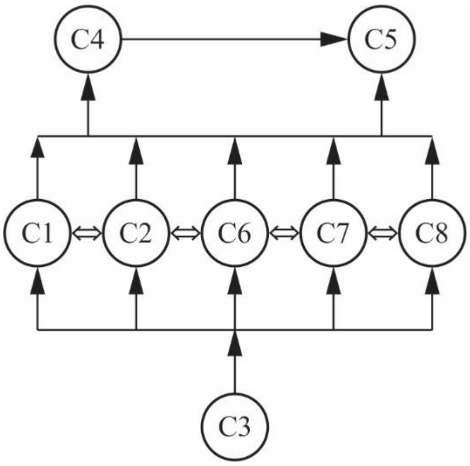

Figure 2. ISM graph with indirect connections removed

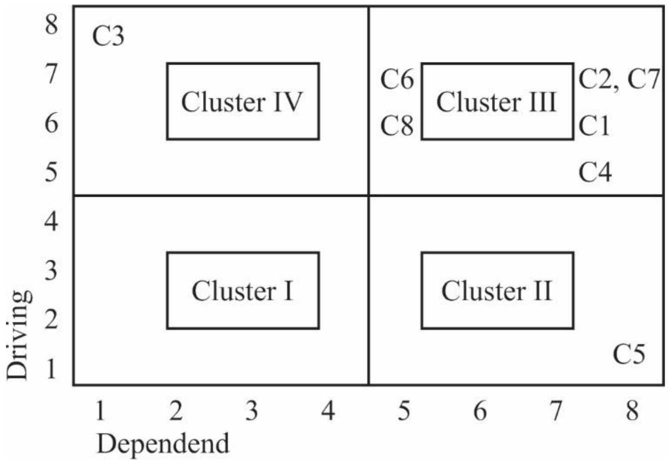

Figure 3. MICMAC analysis - Driving and dependent power diagram

4.2. MICMAC analysis

MICMAC analysis groups criteria into four clusters to understand their nature. These clusters are independent, dependent, linked, and autonomous. Fig. 3 shows the classification of the criteria by using the MICMAC analysis.

Based on the MICMAC analysis, criteria filtering is also facilitated. In fig. 3, Criterion C5 is shown as the most dependent criterion, having very low driving power but maximum dependence. As the most dependent criterion, C5 (Return on investment) can be eliminated from further analysis. Similarly, in the ISM graph in Figure 2, Criterion C5 was also the most dependent one, meaning all other criteria had a certain impact on it. In the first cluster, no criteria were identified as autonomous ones. The most prominent, driving, criterion identified is Criterion C3. According to MICMAC analysis and the ISM graph, C3 (Improvement of construction solutions) has high driving power but low dependence. In the third cluster of linked criteria, other important drivers such as C1, C2, C4, C6, C7, and C8 can be observed. Since the most dependent criterion is Return on nvestment (C5), the conclusion arising both from the ISM graph and MICMAC analysis is that the remaining seven drivers are more significant for the conducting of further research than the use of all eight criteria.

4.3. Application of fuzzy AHP

To determine the weight of the criteria, the fuzzy AHP method was applied. A scale with nine linguistic variables transformed into fuzzy numbers was used (tab. 6). The study involved ten respondents, experts working in the thermal energy sector, academic staff, and the NGO sector in the field of energy efficiency and environmental protection. By using the fuzzy AHP software online [36], the combined weight values of individual criteria are given in tab. 7.

Table 6. Scale table

Code	Linguistics variables	L	M	U
1	Equally important	1	1	1
2	Intermediate value between 1 and 3	1	2	3
3	Slightly important	2	3	4
4	Intermediate value between 3 and 5	3	4	5
5	Important	4	5	6
6	Intermediate value between 5 and 7	5	6	7
7	Strongly important	6	7	8
8	Intermediate value between 7 and 9	7	8	9
9	Extremely important	9	9	9

Table 7. Criterion weight

Rank	Criteria	Criterion name	Criterion weight
1	C1	Increase in utilization rate	0.147
1	C2	Reliability and safety in operation	0.147
4	C3	Improvement of design solutions	0.14
2	C4	Investment cost and value	0.144
3	C6	Environmental impact	0.142
5	C7	Energy cost	0.138
3	C8	Supply reliability	0.142

4.4. Application of fuzzy TOPSIS

For determining the optimal alternative or solution, the fuzzy TOPSIS method was applied in the paper. The fuzzy approach was conducted to include the respondents' answers. The fuzzy scale used in the online fuzzy TOPSIS model [37] is shown in tab. 8.

Table 8. Scale table

Code	Linguistic terms	L	M	U
1	Very weak	0	1	3
2	Weak	1	3	5
3	Average	3	5	7
4	Good	5	7	9
5	Very good	7	9	10

After the creation and normalization of the decision matrix, a normalized matrix with included weights was formed. In the next step, positive and negative ideal solutions were determined, as well as the distance of each measure from the positive and negative ideal solutions. Tab. 9 shows the distance of each measure from the ideal solutions and its closeness coefficient. Measures are ranked by descending values of the closeness coefficient (from highest to lowest). The best measure is the one with the closeness coefficient closest to 1, with subsequent alternatives ranked from the highest to the lowest value.

Table 9. Distance from positive and negative ideal solutions, Closeness coefficient and rank

Measure	Distance from positive ideal	Distance from negative ideal	Ci	Rank
M1	0.222	0.093	0.295	5
M2	0.14	0.175	0.555	2
M3	0.15	0.164	0.523	3
M4	0.051	0.263	0.837	1
M5	0.171	0.144	0.457	4

5. Discussion

To understand the interrelationships of the criteria, the ISM methodology was applied in the study. The digraph (Figure 2) and MICMAC analysis (fig. 3) revealed that the Improvement of construction solutions (C3) is the most influential criterion. In contrast, the Return on investment (C5) was identified as the most dependent criterion. Based on the MICMAC analysis, no criteria were identified in cluster 1, which defines low drive and low dependence. The other criteria were identified in cluster 3 and have high dependence and high driving power. Therefore, Criterion C5, based on its high dependence on other criteria and low driving power (not considered important), was eliminated from the further process of determining the optimal energy efficiency measure for the analyzed thermal power plants.

In the continuation of the study, the weights of the filtered criteria (C1, C2, C3, C4, C6, C7, and C8) were calculated by using the fuzzy AHP method. As shown in Table 7, based on the obtained weights, the increase in utilization rate (C1) and reliability and safety in operation (C2) are the first priorities. The next priorities are the cost and value of the investment (C4), environmental impact (C6), supply reliability (C8), improvement of construction solutions (C3), and energy price (C7).

The weight values were used to calculate the optimal energy efficiency measure by using the fuzzy TOPSIS multi-criteria optimization method. The calculated values are shown in Table 9, indicating that Measure 4 (M4) has a relative closeness of 0.837 and is the top-ranked measure. Measure 1 (M1) has a relative closeness of 0.295 and is ranked as the fifth, or last measure.

The last, or fifth-ranked measure is Measure M1 - Processes in the plant and power grid. Unlike the measures being implemented, Measure M1 has the lowest utilization rate (up to 5%). It relates to processes where greater importance is given to process automation. Although this measure also impacts the reduction of emissions into the atmosphere, it focuses less on the utilization of by-products and increase of utilization rates compared to other measures.

By applying the aforementioned methodology, Thermotechnical processes (Measure 4) have proven to be the optimal solution. This measure involves finding ways to utilize part of the heat energy that is irreversibly lost to the environment. There is a wide range of potential possibilities for its utilization: preheating of combustion air, increasing of the temperature of feed water, drying of coal in the mill inlet channel, and subsequent reheating of steam. By applying Measure 4 (M4), significant heat loss reduction is achieved, thus significantly increasing the utilization rate (up to 15% can be expected). It does not require large investment expenditures and has a very positive effect on the environment compared to the current state.

The conducted research shows that the energy efficiency improvement of thermal power plants is a complex activity that must be approached comprehensively. Due to the complexity of the choice and the inability to compare energy efficiency measures applied to appropriate industrial thermal power plants, these measures are often made based on intuition. However, energy efficiency measures should be made based on exact data. In such situations, a scientific-expert approach is necessary to encompass a large number of relevant technical solutions and, based on appropriate criteria, select the most acceptable solution.

The significant contribution of the conducted research is the developed model that integrates the ISM method, which analyses and filters the set criteria, the fuzzy AHP method for the evaluation of their weights, and the duzzy TOPSIS method of multi-criteria optimization for the determining of the optimal energy efficiency measure in four studied thermal power plants in Bosnia and Herzegovina.

6. Conclusion

The study analyzed the current state of thermal energy control in terms of production, distribution, and consumption in four thermal power plants in Bosnia and Herzegovina. The general conclusion is that certain improvements are necessary in this area.

After conducting the research, the Thermotechnical processes measure was shown to be the optimal solution. It involves finding ways to utilize part of the waste heat that is lost to the environment. Additionally, the research results indicate the priority or order of application of defined measures, depending on the set criteria, on the energy efficiency of the studied thermal power plants.

This research focused on thermal power plants of the same age, with similar or identical technology. Future research should be directed at the application of the developed model for energy efficiency analysis in thermal power plants of different ages, which should show that the age and technical-technological solution of the thermal power plant significantly impact the evaluation of the defined criteria weights. The developed model is universal and, with certain adjustments, applicable for the analysis of the energy efficiency of thermal power plants in various industrial sectors.

Nomenclature

AHP – Analytic Hierarchy Process
ISM – Interpretative Structural Modeling
TOPSIS – Technique for Order Preference by Similarity to Ideal Solution

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