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Fermatean Fuzzy Distance ORCA Methodology for Analysis Solar Water Heating Systems

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Abstract: This study presents an in-depth exploration and evaluation of solar water heating systems, focusing on their technological advancements, economic viability, environmental impact, and practical applications. Solar water heating systems stand as innovative solutions, utilizing solar thermal energy to provide a sustainable and renewable source of hot water. The assessment encompasses an analysis of various collector designs, materials, and efficiency metrics, showcasing the evolution and effectiveness of these systems across different climates and settings. Economic evaluations reveal the cost-effectiveness and potential savings associated with solar water heating, emphasizing reduced energy bills and lower carbon footprints. Environmental assessments highlight the systems' significant contribution to mitigating greenhouse gas emissions and reducing reliance on non-renewable energy sources. Furthermore, real-world applications across residential, commercial, and industrial sectors underscore the versatility and scalability of solar water heating systems. Despite their numerous benefits, challenges persist regarding upfront costs, system integration, and technological limitations. However, strategic research, development, and policy interventions present opportunities to overcome these barriers and promote wider adoption. The findings from this comprehensive assessment provide valuable insights into the significance, challenges, and potential pathways for optimizing solar water heating systems towards a sustainable and energy-efficient future. This study used the Fermantean fuzzy sets with the Operational Competitiveness Rating (ORCA) model for analysis of the criteria and alternatives in solar water heating. We used the 12 criteria and 15 options in this study. The sensitivity analysis is conducted to show the stability of the results.

Keywords: Fermatean Fuzzy Sets, ORCA Method, MCDM, Solar Water Heating Systems.

1. Introduction

Solar water heating systems represent a pioneering stride towards harnessing the inexhaustible power of the sun to fulfil a fundamental human need: hot water. As the world seeks sustainable alternatives to conventional energy sources, solar water heating emerges as a cost-effective, environmentally friendly, and readily available solution that has gained prominence in residential and commercial settings[1]–[3].

At the core of solar water heating systems lies the elegant utilization of solar thermal energy. Through strategically designed solar collectors, these systems capture sunlight, converting it into thermal energy to heat water for various domestic, industrial, and agricultural purposes. This technology alleviates reliance on fossil fuel-based heating and significantly reduces carbon emissions, contributing to the global pursuit of a low-carbon future[4]–[6].

The evolution of solar water heating systems is symbolic of human innovation and technological advancements. Over the years, these systems have undergone transformative developments in collector design, materials, and efficiency, enhancing their effectiveness in diverse climates and geographic locations. From simple batch collectors to advanced evacuated tube systems, the quest for efficiency and affordability continues to drive innovation in this realm[7]–[9].

The significance of solar water heating systems transcends mere technological innovation. They symbolize a paradigm shift in energy consumption patterns, advocating sustainability and energy independence. As societies increasingly embrace renewable energy technologies, these systems are tangible embodiments of the transition towards a cleaner, more resilient energy landscape[10]–[12].

Moreover, solar water heating systems' economic and environmental benefits are palpable. Reduced energy bills, lower operating costs, and diminished greenhouse gas emissions underscore their financial viability and environmental stewardship. Furthermore, decentralising energy production empowers communities to harness their local solar resources, fostering energy self-sufficiency and resilience[13], [14].

A "decision maker (DME)" may rate a choice that has an attribute of 0.8 and a displeasure of 0.65, according to Senapati and Yager's instance. We can now determine that $0.8 + 0.65 > 1$ *and* $(0.8)^2 + (0.65)^2 > 1$, indicating that the intuitionistic fuzzy sets (IFSs) and Pythagorean fuzzy sets (PFSs) do not support this situation[15]–[18]. Senapati and Yager established the concept of Fermatean fuzzy sets (FFs), which provides a comprehensive perspective on FSs, as a way to get over the restrictions of IFSs and PFSs. The "membership grade (MG)" and "non-membership grade (NG)" in FFSs have a cubic sum that equals. This adaptability might aid in resolving uncertainty-related problems, which would make the process more sensible and practical[19]–[22].

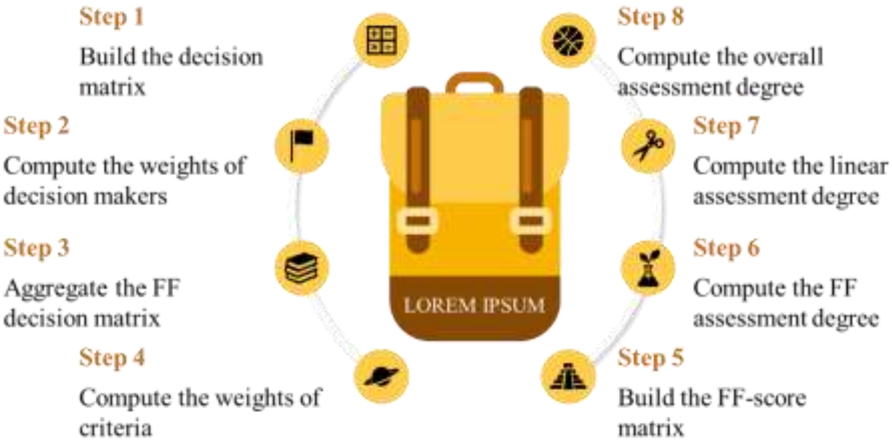

Figure 1. The ORCA model with the FF.

2. Proposed methodology

We introduce the ORCA method with the Fermatean fuzzy (FF) for analysis the solar water heating systems[23]–[26]. Figure 1 shows the steps of the proposed methodology.

Phase 1. Build the decision matrix

The decision matrix is built based on the opinions of the experts between criteria and alternatives.

Phase 2. Compute the weights of decision makers.

$$\gamma_k = \frac{a_k^2(2 - a_k^3 - b_k^3)}{\sum_{k=1}^{l}[a_k^3(2 - a_k^3 - b_k^3)]} \tag{1}$$

Where a and b are elements of FF number.

Phase 3. Aggregate the FF decision matrix

$$f_{ij} = \left(\sqrt[3]{1 - \prod_{k=1}^{l}\left(1 - \left(\left(a_{ij}^{(k)}\right)\right)^3\right)^{\gamma_k}} \quad \prod_{k=1}^{l}\left(b_{ij}^{(k)}\right)^{\gamma_k} \right) \tag{2}$$

Phase 4. Compute the weights of criteria.

Phase 5. Build the FF-score matrix[27], [28].

$$s_{ij} = 0.5\ \left(\left(a_{ij}\right)^3 - \left(b_{ij}\right)^3 + 1\right) \tag{3}$$

Phase 6. Compute the FF assessment degree

$$t_i = \sum_{j \in b} w_j \left(\frac{s_{ij} - \min s_{ij}}{\max s_{ij} - \min s_{ij}}\right) \tag{4}$$

$$e_i = \sum_{j \in b} w_j \left(\frac{\max s_{ij} - s_{ij}}{\max s_{ij} - \min s_{ij}}\right) \tag{5}$$

Phase 7. Compute the linear assessment degree.

$$o_i = t_i - \min t_i \tag{6}$$

$$p_i = e_i - \min e_i \tag{7}$$

Phase 8. Compute the overall assessment degree.

$$u_i = (o_i + p_i) - \min(o_i + p_i) \tag{8}$$

3. Case Analysis

In this section, we introduce the results of the proposed model. We used the 12 criteria and 15 alternatives as[29], [30]:

I. Solar Collector Efficiency: Assess the efficiency of the solar collectors in converting solar energy into heat. This includes evaluating the collector's design, materials, and absorption capabilities.

II. System Performance: Evaluate the overall performance of the system, considering factors like heat output, temperature consistency, and energy yield in different weather conditions.

III. System Durability and Lifespan: Consider the durability of components, such as collectors, piping, and insulation, ensuring they can withstand environmental factors and have a long service life.

IV. Installation and Maintenance: Assess the ease of installation, maintenance requirements, and availability of qualified technicians to ensure optimal system performance over time.

V. Cost-effectiveness: Analyze the initial investment cost, operational costs, and potential energy savings to determine the system's overall cost-effectiveness and payback period.

VI. Reliability and Warranty: Consider the reliability of the system and the warranty offered by manufacturers or installers, ensuring coverage for potential faults or failures.

VII. Scalability and Integration: Evaluate the system's scalability to meet different hot water demand levels and integrate with existing heating systems or infrastructure.

VIII. Environmental Impact: Assess the system's ecological footprint, including its carbon emissions, energy efficiency, and use of environmentally friendly materials.

IX. Regulatory Compliance and Safety: Ensure compliance with local building codes, safety standards, and regulations governing solar water heating systems to guarantee safe installation and operation.

X. Heat Storage and Backup: Assess the capacity and efficiency of heat storage systems and the availability of backup heating options during periods of low solar radiation.

XI. Aesthetics and Integration: Consider solar collectors' visual impact and integration into the building's architecture or surroundings for aesthetic appeal.

XII. Customer Reviews and References: Review customer feedback, testimonials, or references from users who have installed similar systems to gauge real-world performance and satisfaction.

Phase 1. Build the decision matrix by using the FF numbers between criteria and alternatives as shown in Table 1.

Table 1. The decision matrix by using the FF numbers.

	WHC$_1$	**WHC$_2$**	**WHC$_3$**	**WHC$_4$**	**WHC$_5$**	**WHC$_6$**	**WHC$_7$**	**WHC$_8$**	**WHC$_9$**	**WHC$_{10}$**	**WHC$_{11}$**	**WHC$_{12}$**
WHA$_1$	(0.95,0.20)	(0.90,0.30)	(0.85,0.40)	(0.95,0.20)	(0.85,0.40)	(0.90,0.30)	(0.80,0.50)	(0.95,0.20)	(0.90,0.30)	(0.90,0.30)	(0.95,0.20)	(0.95,0.20)
WHA$_2$	(0.90,0.30)	(0.95,0.20)	(0.85,0.40)	(0.70,0.60)	(0.95,0.20)	(0.80,0.50)	(0.90,0.30)	(0.30,0.85)	(0.95,0.20)	(0.95,0.20)	(0.80,0.50)	(0.90,0.30)
WHA$_3$	(0.95,0.20)	(0.80,0.50)	(0.40,0.80)	(0.40,0.80)	(0.30,0.85)	(0.40,0.80)	(0.80,0.50)	(0.30,0.85)	(0.80,0.50)	(0.30,0.85)	(0.70,0.60)	(0.95,0.20)
WHA$_4$	(0.90,0.30)	(0.70,0.60)	(0.95,0.20)	(0.40,0.80)	(0.85,0.40)	(0.20,0.90)	(0.95,0.20)	(0.40,0.80)	(0.20,0.90)	(0.40,0.80)	(0.90,0.30)	(0.85,0.40)
WHA$_5$	(0.85,0.40)	(0.40,0.80)	(0.40,0.80)	(0.40,0.80)	(0.95,0.20)	(0.40,0.80)	(0.20,0.90)	(0.20,0.90)	(0.95,0.20)	(0.30,0.85)	(0.80,0.50)	(0.80,0.50)
WHA$_6$	(0.95,0.20)	(0.80,0.50)	(0.90,0.30)	(0.40,0.80)	(0.80,0.50)	(0.30,0.85)	(0.90,0.30)	(0.40,0.80)	(0.40,0.80)	(0.40,0.80)	(0.85,0.40)	(0.95,0.20)
WHA$_7$	(0.90,0.30)	(0.40,0.80)	(0.80,0.50)	(0.70,0.60)	(0.90,0.30)	(0.40,0.80)	(0.20,0.90)	(0.20,0.90)	(0.90,0.30)	(0.30,0.85)	(0.70,0.60)	(0.90,0.30)
WHA$_8$	(0.85,0.40)	(0.70,0.60)	(0.85,0.40)	(0.40,0.80)	(0.95,0.20)	(0.20,0.90)	(0.80,0.50)	(0.95,0.20)	(0.20,0.90)	(0.80,0.50)	(0.95,0.20)	(0.85,0.40)
WHA$_9$	(0.95,0.20)	(0.80,0.50)	(0.95,0.20)	(0.70,0.60)	(0.85,0.40)	(0.40,0.80)	(0.90,0.30)	(0.20,0.90)	(0.80,0.50)	(0.20,0.90)	(0.40,0.80)	(0.95,0.20)
WHA$_{10}$	(0.90,0.30)	(0.40,0.80)	(0.80,0.50)	(0.40,0.80)	(0.95,0.20)	(0.30,0.85)	(0.90,0.30)	(0.70,0.60)	(0.90,0.30)	(0.95,0.20)	(0.85,0.40)	(0.95,0.20)
WHA$_{11}$	(0.90,0.30)	(0.80,0.50)	(0.90,0.30)	(0.40,0.80)	(0.80,0.50)	(0.40,0.80)	(0.20,0.90)	(0.70,0.60)	(0.30,0.85)	(0.80,0.50)	(0.70,0.60)	(0.90,0.30)
WHA$_{12}$	(0.80,0.50)	(0.40,0.80)	(0.40,0.80)	(0.70,0.60)	(0.40,0.80)	(0.20,0.90)	(0.80,0.50)	(0.20,0.90)	(0.40,0.80)	(0.70,0.60)	(0.40,0.80)	(0.80,0.50)
WHA$_{13}$	(0.40,0.80)	(0.95,0.20)	(0.40,0.80)	(0.90,0.30)	(0.40,0.80)	(0.95,0.20)	(0.20,0.90)	(0.95,0.20)	(0.30,0.85)	(0.70,0.60)	(0.90,0.30)	(0.95,0.20)
WHA$_{14}$	(0.90,0.30)	(0.40,0.80)	(0.80,0.50)	(0.70,0.60)	(0.85,0.40)	(0.70,0.60)	(0.90,0.30)	(0.70,0.60)	(0.80,0.50)	(0.80,0.50)	(0.85,0.40)	(0.90,0.30)
WHA$_{15}$	(0.95,0.20)	(0.80,0.50)	(0.90,0.30)	(0.95,0.20)	(0.40,0.80)	(0.95,0.20)	(0.90,0.30)	(0.95,0.20)	(0.90,0.30)	(0.95,0.20)	(0.90,0.30)	(0.95,0.20)

Phase 2. Compute the weights of decision makers by Eq. (1)

Phase 3. Aggregate the FF decision matrix by Eq. (2).

Phase 4. Compute the weights of criteria as shown in Figure 2.

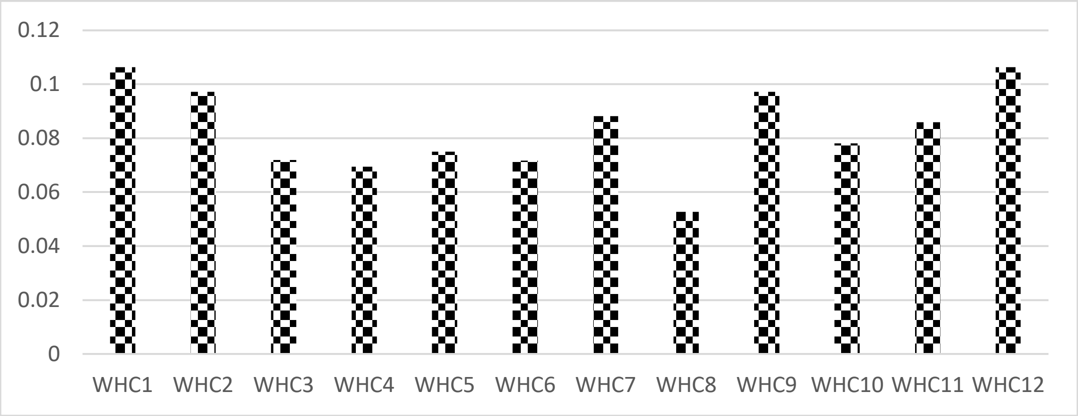

Figure 2. The weights of solar water heating criteria.

Phase 5. Build the FF-score matrix by Eq. (3)

Phase 6. Compute the FF assessment degree by Eqs. (4 and 5) as shown in Table 2.

Table 2. The FF assessment degree.

	WHC_{1}	**WHC_{2}**	**WHC_{3}**	**WHC_{4}**	**WHC_{5}**	**WHC_{6}**	**WHC_{7}**	**WHC_{8}**	**WHC_{9}**	**WHC_{10}**	**WHC_{11}**	**WHC_{12}**
WHA_{1}	0.1063	0.0862	0.0553	0.0695	0.0594	0.065	0.0622	0.0527	0.0881	0.0707	0.0859	0.1063
WHA_{2}	0.0943	0.0972	0.0553	0.0308	0.0751	0.0506	0.0799	0.0045	0.0972	0.0781	0.0553	0.0724
WHA_{3}	0.1063	0.0626	0	0	0	0.0125	0.0622	0.0045	0.0686	0.0067	0.0381	0.1063
WHA_{4}	0.0943	0.0431	0.0719	0	0.0594	0	0.0881	0.0092	0	0.0136	0.0761	0.0375
WHA_{5}	0.0818	0	0	0	0.0751	0.0125	0	0	0.0972	0.0067	0.0553	0
WHA_{6}	0.1063	0.0626	0.0637	0	0.0509	0.0061	0.0799	0.0092	0.0169	0.0136	0.0661	0.1063
WHA_{7}	0.0943	0	0.0463	0.0308	0.0674	0.0125	0	0	0.0881	0.0067	0.0381	0.0724
WHA_{8}	0.0818	0.0431	0.0553	0	0.0751	0	0.0622	0.0527	0	0.0551	0.0859	0.0375
WHA_{9}	0.1063	0.0626	0.0719	0.0308	0.0594	0.0125	0.0799	0	0.0686	0	0	0.1063
WHA_{10}	0.0943	0	0.0463	0	0.0751	0.0061	0.0799	0.0284	0.0881	0.0781	0.0661	0.1063
WHA_{11}	0.0943	0.0626	0.0637	0	0.0509	0.0125	0	0.0284	0.0083	0.0551	0.0381	0.0724
WHA_{12}	0.0684	0	0	0.0308	0.0073	0	0.0622	0	0.0169	0.0421	0	0
WHA_{13}	0	0.0972	0	0.0616	0.0073	0.0717	0	0.0527	0.0083	0.0421	0.0761	0.1063
WHA_{14}	0.0943	0	0.0463	0.0308	0.0594	0.0387	0.0799	0.0284	0.0686	0.0551	0.0661	0.0724
WHA_{15}	0.1063	0.0626	0.0637	0.0695	0.0073	0.0717	0.0799	0.0527	0.0881	0.0781	0.0761	0.1063

Phase 7. Compute the linear assessment degree by Eqs. (6 and 7).

Phase 8. Compute the overall assessment degree by Eqs. (8) as shown in Figure 3. We show the alternative 1 is the best and alternative 12 is the worst.

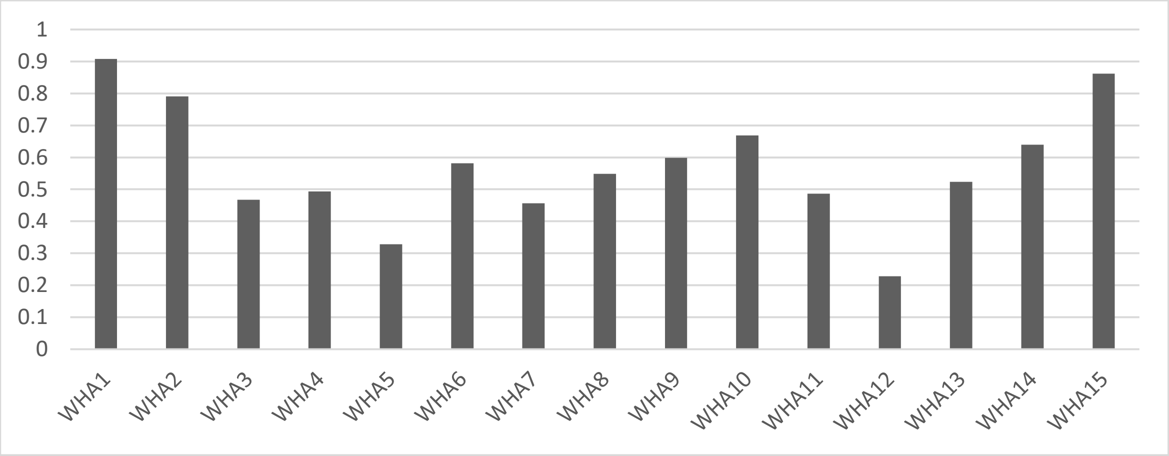

Figure 3. The overall assessment degree.

We change the weights of criteria to ensure the stability of the results. We change the weights of criteria by the 12 cases as shown in Figure 4. Then compute the rank of alternatives as shown in Figure 5. The results show the results are stable.

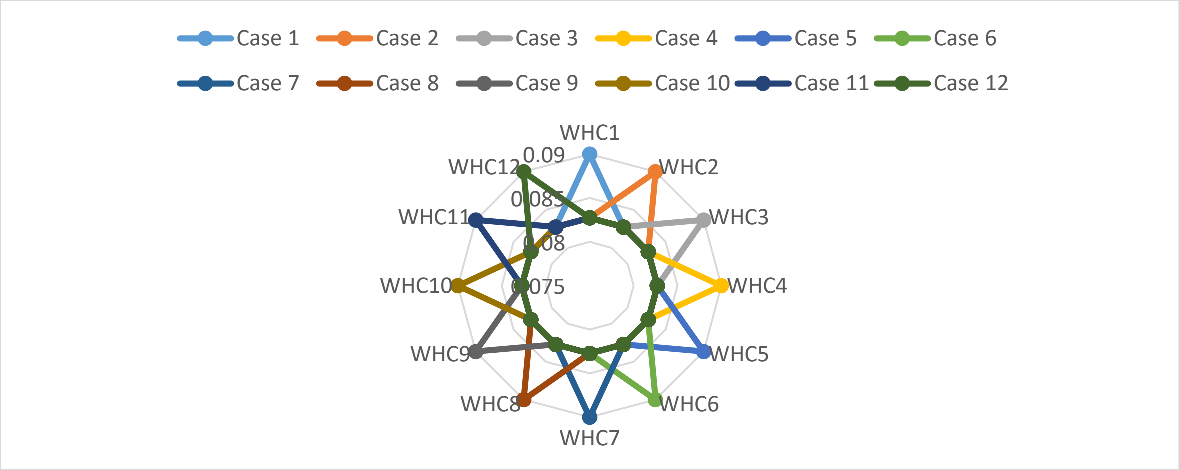

Figure 4. The 12 cases of weights of criteria.

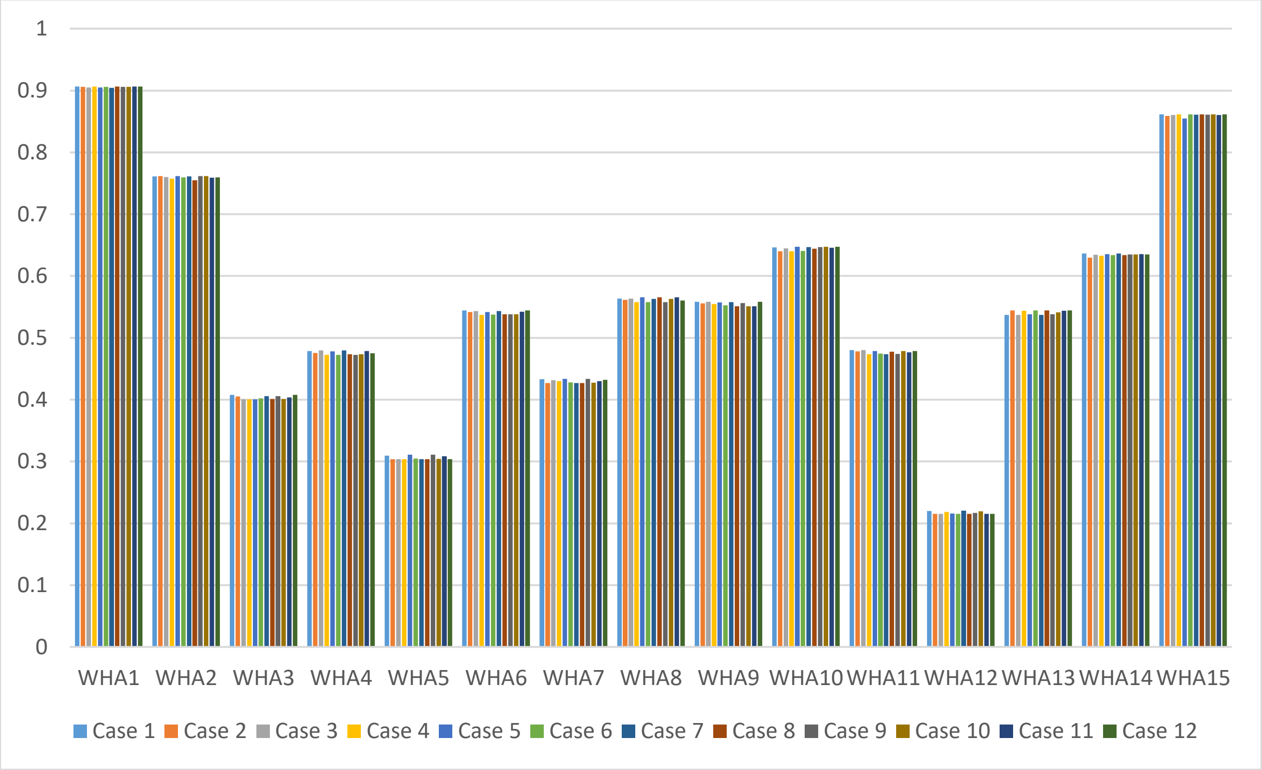

Figure 5. The rank of alternatives.

4. Conclusions

The evaluation of solar water heating systems unveils a compelling narrative of progress, potential, and challenges in renewable energy technologies. Technologically, advancements in collector designs, absorber materials, and system efficiency showcase a promising trajectory towards higher performance and reliability across diverse environmental conditions. Economic assessments underscore the substantial cost savings and economic benefits associated with solar water heating, albeit challenges regarding initial investment costs remain a hurdle. Nonetheless, the environmental benefits, including reduced greenhouse gas emissions and minimized reliance on finite energy sources, reaffirm the systems' pivotal role in sustainability efforts. Practical applications in various sectors emphasize the adaptability and versatility of solar water heating systems, offering scalable solutions for diverse hot water demands. As technology evolves, addressing challenges related to cost, integration, and technological limitations will be imperative. Collaborative efforts in research, development, policy incentives, and public awareness campaigns are vital in surmounting these challenges and accelerating the adoption of solar water heating systems. The path towards a sustainable future powered by solar energy remains promising, propelled by the transformative potential of solar water heating systems and their contribution to a cleaner, more resilient energy landscape. We used the FF to deal with uncertain information. Then, we employed the FF with the ORCA model for analysis of the criteria and alternatives in the solar water heating systems. We used 12 criteria and 15 alternatives. The main results show that alternative 1 is the best and alternative 12 is the worst.

Author Contributions

All authors contributed equally to this work.

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This article does not contain any studies with human participants or animals performed by any of the authors.

Conflicts of Interest

The authors declare that there is no conflict of interest in the research.

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Not applicable.

Data Availability Statement

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