

# Multi-Criteria Assessment of Renewable Energy Technologies for Solar Buildings Using WASPAS Method

Shilpa Kathad<sup>1\*</sup>, Kishan Bhayani<sup>2</sup>

## Abstract

*This research comprehensively evaluates renewable energy alternatives for solar buildings using the WASPAS multi-criteria decision-making framework. The analysis covers six distinct energy technologies: geothermal heat pumps, wind turbines, biomass heating systems, micro-hydro installations, fuel cells and building-integrated energy efficiency systems. These options are assessed against four key criteria: energy efficiency, economic viability, environmental sustainability and technical feasibility. The WASPAS methodology combines both summative and multiplicative techniques to produce reliable rankings. His findings reveal micro-hydro as the top ranked solution, receiving a score of 0.79640 due to its superior technical viability and energy efficiency. Biomass heating systems came in second place with a score of 0.80908, demonstrating strong performance across all evaluation parameters. Fuel cells came in third place (0.56218), while wind turbines, building-integrated energy efficiency systems, and geothermal heat pumps ranked fourth to sixth with scores of 0.54865, 0.52517, and 0.59406, respectively. To maintain objectivity, each evaluation criterion received an equal weight of 0.25, ensuring that all factors were considered in balance. The research emphasizes the critical need to consider site-specific conditions, resource availability, and project goals when selecting energy technologies for solar buildings. In conclusion, this work improves decision-making methods for sustainable building design and contributes to efforts aimed at achieving net-zero energy structures in the face of global climate concerns.*

**Keywords:** Solar buildings, renewable energy systems, energy efficiency, sustainable architecture, micro hydropower, biomass heating, net-zero energy, MCDM

## INTRODUCTION

Solar buildings represent a significant step forward in integrating sustainable architecture and renewable energy systems. With global concerns including climate change, rising energy costs, and the need to reduce carbon footprints, solar buildings offer a viable solution by combining energy conservation with environmentally conscious architectural approaches [1]. These structures utilize solar energy to meet their energy needs, thereby introducing an innovative paradigm in contemporary

construction [2]. A solar building is defined as any structure that captures, stores, and utilizes solar energy for various purposes, including power generation, climate control, and lighting [3]. In contrast to conventional buildings that rely on grid-supplied electricity, which is generated primarily from fossil fuels, solar buildings utilize technologies such as photovoltaic arrays, solar thermal installations, and passive solar architecture to reduce their reliance on external power sources [4]. These implementations range from basic rooftop solar installations to sophisticated net-zero energy structures that generate energy equivalent to their annual consumption [5]. Solar building architecture typically utilizes two primary

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approaches: active and passive solar systems. Active structures rely on mechanical and electrical equipment, including photovoltaic arrays, whereas passive methods use architectural design and positioning to naturally control temperature and light [6]. Passive solar features include strategically positioned windows, thermal mass elements that absorb and release heat, natural air circulation, and carefully designed overhangs to maximize the use of seasonal sunlight [7]. By transforming the field of building-integrated photovoltaics, contemporary solar panels demonstrate high efficiency, cost effectiveness, and adaptability [8]. This innovation enables solar cells to be directly incorporated into building materials, such as roof tiles, exterior walls, and glazing, allowing structures to generate electricity while maintaining their visual appeal. Energy storage is another important component of solar buildings [9]. For example, lithium-ion battery systems enable structures to retain surplus energy generated during peak sunlight hours for use during periods when solar power availability is low, thereby improving energy autonomy and sustainability [10]. This capability is particularly beneficial in areas that experience variable weather conditions. In addition, sophisticated energy management platforms optimize consumption by regulating the power supply according to the immediate demand and supply [11]. The environmental benefits of solar buildings are significant. By generating clean, renewable electricity on-site, they reduce the greenhouse gas emissions associated with conventional energy generation [12]. A single, sustainable, solar-equipped home can prevent several tons of CO<sub>2</sub> emissions each year, equivalent to the carbon sequestration of hundreds of trees [13]. Furthermore, solar buildings contribute to reducing air and water pollution, stress on the power infrastructure during periods of high demand, and conserving natural resources, all of which support global sustainability goals and climate initiatives [14]. Solar buildings are gaining traction economically. Despite the increased upfront installation costs compared to traditional construction, the extended-term financial benefits are significant. Solar structures can eliminate or drastically reduce utility costs, provide protection against future energy price increases, and often qualify for government incentives, including tax breaks and financial rebates. The payback period for solar systems has decreased significantly, with many installations recovering costs within seven to twelve years, followed by decades of continued savings and profit generation. Additionally, properties with solar technology command higher market values and experience faster sales than similar properties without such features. At the community level, the proliferation of solar buildings provides long-term benefits. Communities that adopt solar technologies foster local employment growth in sectors such as system installation, maintenance, and manufacturing. Furthermore, energy self-sufficiency at the building level strengthens community resilience and security by reducing dependence on external power grids [15].

## **MATERIALS AND METHOD**

### **Geothermal Heat Pumps**

These systems utilize the Earth's constant underground temperature to provide efficient climate control for buildings. By circulating fluids within underground pipe networks, they extract or deposit thermal energy into the structure, thereby significantly reducing energy consumption.

### **Wind Turbines**

These devices convert the kinetic energy of wind into electrical energy through rotating blades connected to electrical generators. They can be used as individual units or in extensive arrays, generating pollution-free, renewable electricity with no fuel requirements or emissions.

### **Biomass Heating Systems**

These installations generate thermal energy by burning organic materials, including wood pellets, wood chips, and agricultural residues. This fuel source is considered carbon-neutral because the carbon dioxide released during combustion is balanced by the CO<sub>2</sub> absorbed during plant growth.

### **Micro-Hydro**

Small hydroelectric installations generate electricity using water flowing from streams or waterways, typically producing less than 100 kW. These configurations are particularly advantageous in isolated areas, providing reliable, sustainable electricity with minimal environmental disruption compared to large-scale hydroelectric facilities.

### **Fuel Cells**

These electrochemical units convert hydrogen and oxygen into electrical energy, producing only water vapor and heat as outputs. They offer a clean and efficient power solution suitable for various applications, from transportation to residential buildings and small electronic devices.

### **Building-Integrated Energy**

This strategy integrates power generation technologies, such as photovoltaic systems, directly into the architectural elements. Solar modules embedded within roofing materials or window systems enable structures to generate their own electricity. This technique improves both usability and visual design, while simultaneously reducing the environmental footprint and energy costs.

### **Energy Efficiency**

Energy efficiency involves reducing power consumption while maintaining the operational performance levels. This is accomplished through advanced technologies, improved insulation methods, and better equipment, resulting in reduced costs, environmental impacts, and resource conservation without sacrificing comfort or output.

### **Economic Viability**

Economic viability refers to a project's ability to provide sufficient financial returns to cover the initial capital investment, ongoing operating costs, and inherent risks. It involves evaluating future revenue streams, cost recovery timelines, and market dynamics to ensure financial sustainability and profitability.

### **Environmental Impact**

Environmental impact includes the effects of human activities on the natural environment, such as pollution, resource depletion, and climate change. It includes the effects on air quality, water bodies, soil structure, ecosystems, and biological diversity. Assessing environmental impact is essential to minimize damage, preserve ecosystems for future generations and promote sustainable practices.

### **Technical Reliability**

Technical reliability describes the ability of systems, machines, or technologies to operate consistently and reliably throughout their operational lifetime under designated conditions. It involves assessing factors such as longevity, failure frequency, maintenance demand, and comprehensive performance. High technical reliability ensures minimal operational interruptions, reduces maintenance costs, ensures safe operation and fosters lasting user confidence in technical performance.

### **WASPAS Method**

The WASPAS algorithm, introduced in 2012 by researchers Edmunds Kazimierz Saatsakis, Zenonas Turkish, and Jurist Anduceviczyn, represents a significant advance in multi-criteria decision-making frameworks [16]. It has quickly gained recognition as a useful tool for evaluating alternatives to multiple competing factors. WASPAS combines two conventional MCDM approaches, the weighted sum model and the weighted product model, by exploiting their combined advantages and minimizing their weaknesses [17]. The basic principle of WASPAS is to combine sum-based and multiplicative decision-making methods. While conventional MCDM techniques rely solely on additive or multiplicative aggregation, WASPAS recognizes that each approach offers unique advantages depending on the decision-making context [18]. Using the  $\lambda$  parameter, WASPAS establishes an adaptive framework that is adaptable to various decision situations. The  $\lambda$  coefficient typically varies between 0 and 1, where a value of 1 corresponds to the WPM, 0 indicates the WSM, and intermediate values constitute a hybrid method that balances the two techniques [19]. The implementation of the WASPAS approach follows a systematic and well-defined procedure. It begins with the creation of a decision matrix, where detailed and accurate data collection is important because the quality of the outcomes depends significantly on the accuracy of the input information [20]. To allow for a comparison across criteria, especially when

these factors are measured using different units or scales of measurement, the decision matrix undergoes normalization [21], [22]. This standardization process converts the values into dimensionless statistics, facilitating cross-criteria comparisons. Following normalization, weights are assigned to individual criteria to reflect the decision-maker's priorities [23]. These weights can be established through techniques including the analytic hierarchy process, the entropy method, or professional judgment, and must be properly coordinated to ensure the appropriate contribution of each criterion to the outcome [24]. Subsequently, dual calculations are performed for each alternative: one using the weighted sum model and the other using the weighted product model [25]. The WSM determines the weighted sum of the normalized statistics for each option, whereas the WPM calculates the weighted product for each option. Ultimately, the WASPAS technique combines these results to produce a robust evaluation measure that includes the  $\lambda$  parameter [26]. The primary advantage of the WASPAS approach is its ability to provide more reliable and accurate results than those obtained using either the WSM or WPM independently. Studies have confirmed that this combined method produces more consistent rankings when dealing with complex decision-making situations involving multiple alternatives [27]. In addition, the  $\lambda$  parameter provides adaptability, enabling decision-makers to adjust the balance between the additive and multiplicative components according to the problem characteristics [28]. This versatility has established WASPAS as widely applicable in domains including engineering, construction project evaluation, vendor selection, site determination, employee performance evaluation, and technology evaluation [29]. Another significant strength of WASPAS is its straightforwardness and user-friendliness. Compared to alternative MCDM approaches, it is very simple to understand and implement, requiring only basic knowledge of its mathematical foundations. This accessibility makes WASPAS practical, even for users with a limited mathematical background [30].

## RESULT AND DISCUSSION

Table 1 compares the performance of six renewable energy technologies for solar buildings based on four key criteria: energy efficiency, economic viability, environmental impact, and technical feasibility. The results indicate that micro hydropower achieves the highest energy efficiency rating of 143, whereas fuel cells demonstrate the best economic viability with a score of 153. Biomass heating systems and wind turbines maintain relatively balanced performance across several categories. In particular, geothermal heat pumps recorded a low environmental impact score of 54, whereas building-integrated energy efficiency systems, despite achieving the highest energy efficiency rating of 156, showed limited technical feasibility with a score of 56. Overall, each technology demonstrated unique advantages and limitations across the assessed criteria.

Figure 1 illustrates the comparative performance of six renewable energy technologies applicable to solar buildings, as assessed using four key criteria: energy efficiency, economic viability, environmental impact, and technical feasibility. The data revealed distinct performance patterns, with each technology exhibiting unique advantages and limitations. In particular, micro hydropower shows the best energy efficiency at 143, while fuel cells achieve the highest economic viability score of 153. Building-integrated energy efficiency systems recorded the highest energy efficiency rating of 156; however, they showed relatively weak technical viability with a score of 56.

**Table 1.** Solar building.

|                                       | Energy efficiency | Economic viability | Environmental impact | Technical reliability |
|---------------------------------------|-------------------|--------------------|----------------------|-----------------------|
| Geothermal Heat Pumps                 | 121               | 98                 | 54                   | 68                    |
| Wind Turbines                         | 123               | 66                 | 75                   | 78                    |
| Biomass Heating Systems               | 134               | 76                 | 66                   | 88                    |
| Micro Hydropower                      | 143               | 85                 | 74                   | 45                    |
| Fuel Cells                            | 153               | 94                 | 33                   | 66                    |
| Building-Integrated Energy Efficiency | 156               | 88                 | 66                   | 56                    |

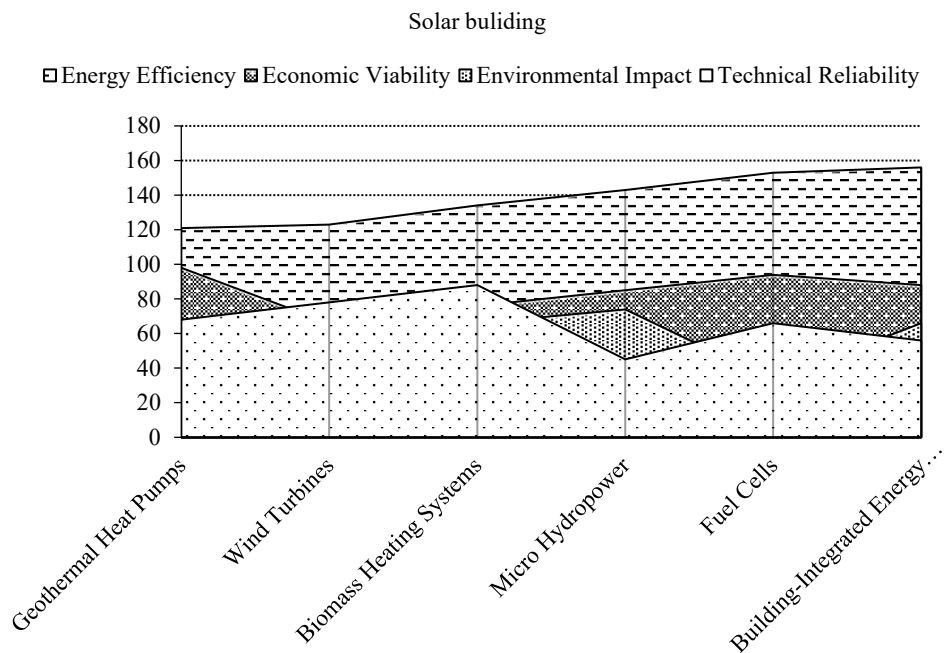


**Figure 1.** Solar building.

**Table 2.** Performance value.

|                                       | Performance value |         |         |         |
|---------------------------------------|-------------------|---------|---------|---------|
| Geothermal Heat Pumps                 | 0.77564           | 1.00000 | 0.72000 | 0.66176 |
| Wind Turbines                         | 0.78846           | 0.67347 | 1.00000 | 0.57692 |
| Biomass Heating Systems               | 0.85897           | 0.77551 | 0.88000 | 0.51136 |
| Micro Hydropower                      | 0.91667           | 0.86735 | 0.98667 | 1.00000 |
| Fuel Cells                            | 0.98077           | 0.95918 | 0.44000 | 0.68182 |
| Building-Integrated Energy Efficiency | 1.00000           | 0.89796 | 0.88000 | 0.80357 |

**Table 3.** Weight.

| Weight |      |      |      |
|--------|------|------|------|
| 0.25   | 0.25 | 0.25 | 0.25 |
| 0.25   | 0.25 | 0.25 | 0.25 |
| 0.25   | 0.25 | 0.25 | 0.25 |
| 0.25   | 0.25 | 0.25 | 0.25 |
| 0.25   | 0.25 | 0.25 | 0.25 |
| 0.25   | 0.25 | 0.25 | 0.25 |

Table 2 presents the normalized performance metrics of the six renewable energy technologies for solar buildings assessed across four criteria. The results indicate that micro hydropower achieves the highest technical feasibility score of 1.00000 and demonstrates exceptional environmental impact performance at 0.98667. Fuel cells demonstrate strong economic feasibility with a score of 0.95918; however, their environmental impact is significantly lower at 0.44000. Building-integrated energy efficiency systems achieve the highest energy efficiency score of 1.00000 but show relatively weak technical feasibility at 0.80357. Biomass heating systems exhibited consistent and well-rounded performance across all criteria.

Table 3 presents the weight distribution used for the four evaluation criteria: energy efficiency, economic viability, environmental impact, and technical feasibility. Each criterion was assigned a

uniform weight of 0.25, which facilitated a balanced and equal assessment across all parameters. This equal weighting method implies that no single criterion is prioritized over the others in assessing the performance of renewable energy technologies for solar buildings, thereby enabling an unbiased and complete comparative analysis.

Table 4 shows the weighted normalized decision matrix using the Weighted Sum Model for six renewable energy technologies assessed using four criteria. The values represent the weighted contribution of each technology to the total score, which includes equal criterion weights of 0.25. Building-integrated energy efficiency systems achieved the highest weighted score in energy efficiency at 0.25000, while micro-hydropower demonstrated the best performance in technical feasibility with a similar score of 0.25000. Notably, fuel cells, while demonstrating strong economic feasibility, received relatively low scores in the environmental impact category.

Table 5 presents the weighted normalized decision matrix calculated using the Weighted Product Model for the six renewable energy technologies assessed across four criteria. The results indicate that micro hydropower achieved the highest score in economic viability at 1.00000, although its performance across the remaining criteria was modest. Biomass heating systems show exceptional environmental impact performance with a score of 1.00000 and show strong overall results across all parameters. Fuel cells show strong performance in both economic viability and technical viability; however, their environmental impact scores are relatively low. Geothermal heat pumps and wind turbines showed consistent and well-rounded performance across the assessment criteria.

**Table 4.** Weighted normalized decision matrix (WSM).

| Geothermal heat pumps                 | 0.19391 | 0.25000 | 0.18000 | 0.16544 |
|---------------------------------------|---------|---------|---------|---------|
| Wind Turbines                         | 0.19712 | 0.16837 | 0.25000 | 0.14423 |
| Biomass Heating Systems               | 0.21474 | 0.19388 | 0.22000 | 0.12784 |
| Micro Hydropower                      | 0.22917 | 0.21684 | 0.24667 | 0.25000 |
| Fuel Cells                            | 0.24519 | 0.23980 | 0.11000 | 0.17045 |
| Building-Integrated Energy Efficiency | 0.25000 | 0.22449 | 0.22000 | 0.20089 |

**Table 5.** Weighted normalized decision matrix (WPM).

|                                       | Weighted normalized decision matrix |         |         |         |
|---------------------------------------|-------------------------------------|---------|---------|---------|
| Geothermal Heat Pumps                 | 0.88416                             | 0.71436 | 0.73690 | 1.00000 |
| Wind Turbines                         | 0.90360                             | 0.90005 | 0.80054 | 0.92962 |
| Biomass Heating Systems               | 0.95544                             | 0.94015 | 1.00000 | 0.96161 |
| Micro Hydropower                      | 1.00000                             | 1.00000 | 0.78361 | 0.91276 |
| Fuel Cells                            | 0.98581                             | 0.97003 | 0.75711 | 0.87642 |
| Building-Integrated Energy Efficiency | 0.93910                             | 0.82744 | 0.72124 | 0.83737 |

**Table 6.** Preference score (WSM) (WPM).

|                                       | Preference score (WSM) | Preference score (wpm) |
|---------------------------------------|------------------------|------------------------|
| Geothermal Heat Pumps                 | 0.78935                | 0.46543                |
| Wind Turbines                         | 0.75971                | 0.60525                |
| Biomass Heating Systems               | 0.75646                | 0.86378                |
| Micro Hydropower                      | 0.94267                | 0.71525                |
| Fuel Cells                            | 0.76544                | 0.63453                |
| Building-Integrated Energy Efficiency | 0.89538                | 0.46929                |

Table 6 presents the preference scores for the six renewable energy technologies calculated using both the Weighted Sum Model and Weighted Product Model methods. Micro hydropower achieved the highest WSM preference score of 0.94267, reflecting its strong overall performance across the evaluation criteria. Biomass heating systems demonstrated the best performance under the WPM approach, with a score of 0.86378, highlighting their exceptional environmental performance and balanced characteristics. Building-integrated energy efficiency systems achieved a strong WSM score of 0.89538; however, their WPM score was significantly lower at 0.46929, indicating varying performance outcomes depending on the evaluation method used.

Figure 2 provides a visual comparison of the preference scores for the six renewable energy technologies assessed using both the Weighted Joint Model and Weighted Product Model methods. Micro hydropower shows the best performance under the WSM approach with a score of 0.94267; however, its WPM score is significantly lower (0.71525). Biomass heating systems achieved the highest WPM preference score of 0.86378, whereas fuel cells and wind turbines showed relatively consistent performance under both assessment methods. Building-integrated energy efficiency systems achieve strong results under the WSM (0.89538) but show significantly weaker performance under the WPM (0.46929).

Table 7 presents the WASPAS coefficients for the six renewable energy technologies, indicating their comprehensive performance across all assessment criteria. Biomass heating systems achieved the highest WASPAS coefficient of 0.80908, with micro hydropower close behind at 0.79640, both showing strong multi-criteria performance. Geothermal heat pumps (0.59406) and fuel cells (0.56218) received lower rankings, primarily because of their weak environmental impact scores. Wind turbines and building-integrated energy efficiency systems showed moderate overall performance, recording WASPAS coefficients of 0.54865 and 0.52517, respectively.

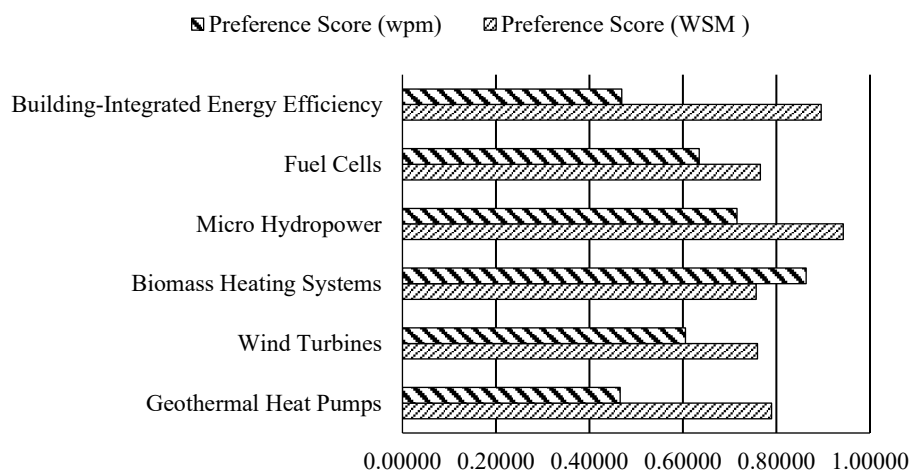


**Figure 2.** Preference score (WSM) (WPM).

**Table 7.** WASPAS coefficient.

|                                       | WASPAS Coefficient |
|---------------------------------------|--------------------|
| Geothermal Heat Pumps                 | 0.59406            |
| Wind Turbines                         | 0.54865            |
| Biomass Heating Systems               | 0.80908            |
| Micro Hydropower                      | 0.79640            |
| Fuel Cells                            | 0.56218            |
| Building-Integrated Energy Efficiency | 0.52517            |

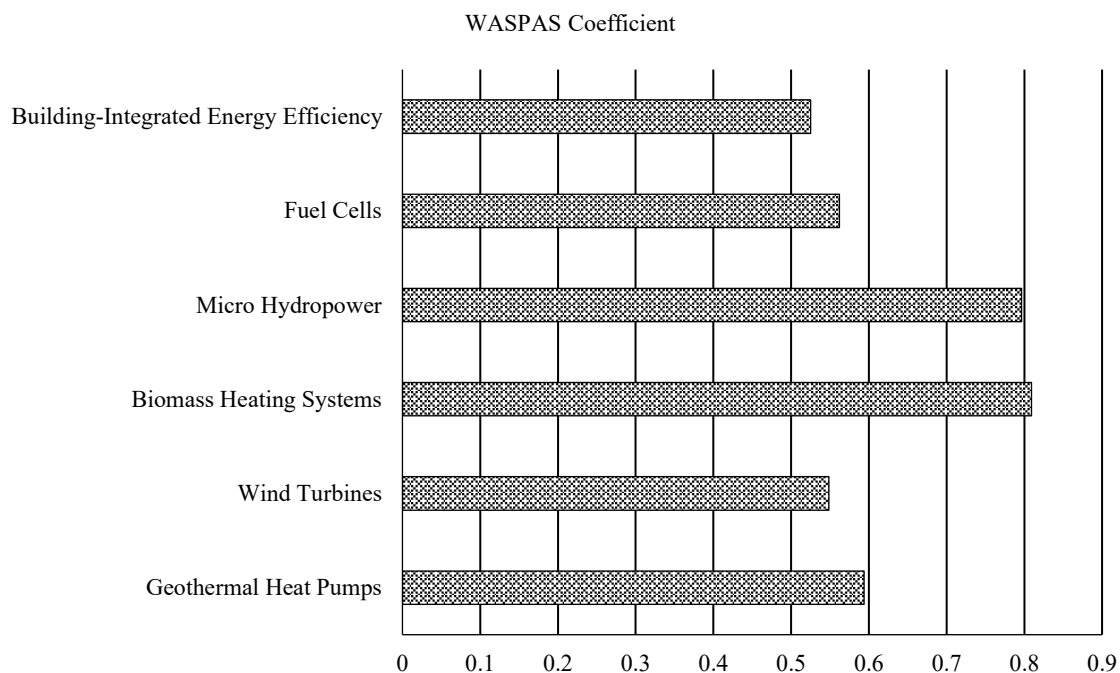


**Figure 3.** WASPAS coefficient.

**Table 8.** Rank.

|                                       | Rank |
|---------------------------------------|------|
| Geothermal Heat Pumps                 | 6    |
| Wind Turbines                         | 4    |
| Biomass Heating Systems               | 2    |
| Micro Hydropower                      | 1    |
| Fuel Cells                            | 3    |
| Building-Integrated Energy Efficiency | 5    |

Table 8 presents the final rankings of the six renewable energy technologies derived from the WASPAS assessment. Micro hydropower ranks first (1st), biomass heating systems second, and fuel cells third. Wind turbines were ranked fourth, and building-integrated energy efficiency systems were ranked fifth. Geothermal heat pumps received the lowest ranking (6th), indicating that although they show satisfactory performance on some criteria, they are relatively less competitive when fully evaluated against other technologies.

Figure 3 provides a visual representation of the WASPAS coefficients for the six renewable-energy technologies. Biomass heating systems achieved the highest coefficient at 0.80908, with micro hydropower in second place at 0.79640, both showing strong comprehensive performance across the assessment criteria. Geothermal heat pumps (0.59406) and fuel cells (0.56218) receive lower coefficients, primarily due to their shortcomings in environmental impact performance.

Figure 4 illustrates the hierarchical rankings of the six renewable energy technologies established by the WASPAS assessment system. Micro hydropower occupied the top position (1st), followed by biomass heating systems (2nd) and fuel cells (3rd). Wind turbines, building-integrated energy efficiency systems, and geothermal heat pumps were ranked fourth, fifth, and sixth, respectively. These rankings represent a comprehensive performance assessment of each technology across all the assessed criteria.

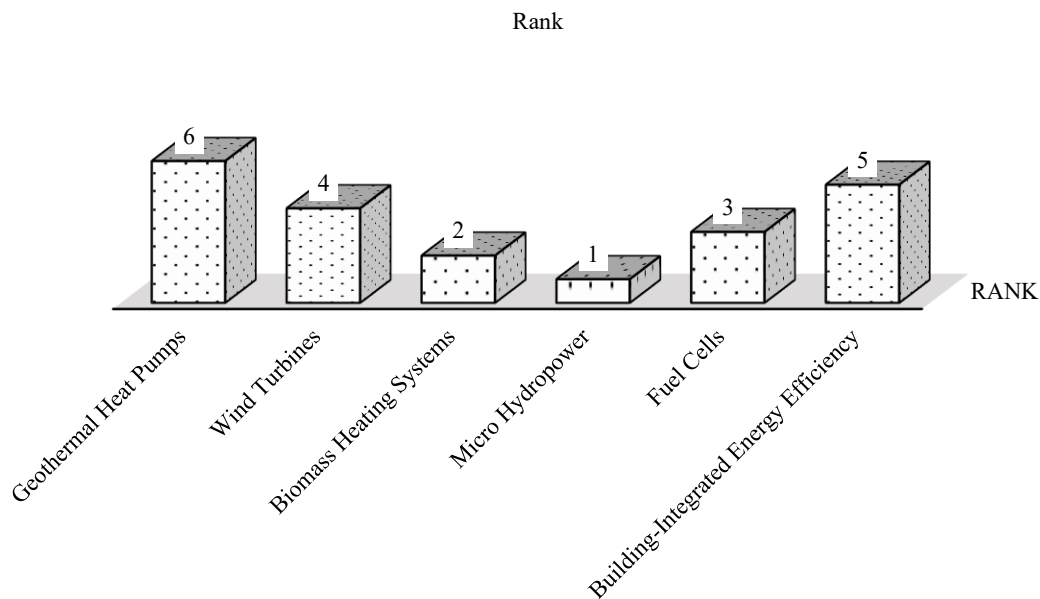


**Figure 4.** Rank.

## CONCLUSION

This study conducted a comprehensive evaluation of six renewable energy alternatives for solar buildings using key WASPAS parameters: energy efficiency, economic viability, environmental impact, and technical feasibility. This comprehensive study provides important findings on the performance characteristics and suitability of each technology for sustainable construction. Micro-water systems achieved the highest ranking with a WASPAS score of 0.79640, showing excellent performance in technical feasibility and energy efficiency. This indicates that when implementation conditions are favorable, micro-water installations provide excellent results across several evaluation parameters. Biomass heating systems came in second place with a score of 0.80908, demonstrating strong and reliable performance, particularly with regard to energy efficiency and environmental sustainability, positioning them as strong competitors to structures with accessible befool sources. Fuel cells ranked third (0.56218), offering significant economic viability and energy efficiency, although they face some environmental considerations. Wind turbines ranked fourth (0.54865), showing a particular strength in environmental performance metrics. Building-integrated energy efficiency systems ranked fifth (0.52517), while geothermal heat pumps ranked sixth (0.59406), showing consistent performance across all assessment categories. The rankings illustrate the complex balancing considerations inherent in the selection of renewable energy solutions for building applications. Each assessment parameter was assigned a balanced weight (0.25), ensuring that technology, economics, environment, and reliability aspects receive equal consideration. The results provide practical directions for architects, engineers, and policymakers involved in sustainable building planning. This research underscores the need for context-specific decisions influenced by factors such as geographic location, resource access, building specifications, and project objectives, highlighting that no single technology demonstrates superiority across all assessment dimensions.

Subsequent research could build on this study by incorporating sensitivity analyses using different weight configurations, examining additional parameters such as maintenance demands and operational longevity, and evaluating integrated systems that combine multiple renewable technologies. In summary, this study emphasizes the importance of systematic decision-making methods in advancing sustainable construction, realizing net-zero energy construction objectives, and addressing global climate change imperatives.

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