Multi-Criteria Decision Analysis for Evaluating the Effectiveness of Alternative Energy Sources in China

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Abstract: The transition to renewable energy sources is crucial for mitigating the impacts of climate change and achieving sustainable development goals. In China, the rapid industrialization and urbanization have led to an increasing demand for energy, highlighting the urgent need to transition to alternative energy sources. This study aims to evaluate the effectiveness of alternative energy sources in China, considering multiple criteria such as cost, environmental impact, energy output, reliability, and scalability. We employed a Multi-Criteria Decision Analysis (MCDA) approach to compare and rank different energy sources based on these criteria. Our findings indicate that wind energy is the most effective alternative energy source overall due to its relatively low cost, high efficiency, moderate environmental impact, good scalability, and high reliability. However, geothermal energy had the lowest levelized cost of electricity (LCOE), while hydro energy performed well in terms of efficiency and reliability. The environmental impact of wind energy was found to be moderate but still less severe compared to other energy sources. Our study provides important insights into the trade-offs and considerations that policymakers and industry leaders must make when selecting which energy sources to prioritize. The findings highlight the need for a comprehensive and integrated approach to energy policy that balances economic, environmental, and social considerations. In conclusion, this study contributes to the literature by emphasizing the importance of considering multiple criteria when evaluating alternative energy sources. Our findings can inform policy decisions regarding the development of a sustainable and reliable energy mix in China, and have important implications for other countries seeking to transition to renewable energy sources.

Keywords: alternative energy; economical-mathematical model; China; solar energy; wind energy; hydropower

1. Introduction

The need for transitioning to renewable energy sources has become increasingly urgent due to the negative environmental impacts of traditional fossil fuels [1], such as greenhouse gas emissions that contribute to climate change [2]. In recent years, there has been a growing recognition of the importance of renewable energy sources as a means of achieving sustainable development goals [3,4], including reducing carbon emissions [5], increasing energy security [6,7], and promoting economic growth [8,9]. The global demand for energy is increasing rapidly, and there is a growing need for alternative energy sources to supplement traditional fossil fuels [10,11]. Alternative energy sources have become increasingly important despite the challenges posed by climate change and the finite nature of traditional fossil fuels, e.g., ([12,13]). Therefore, the transition to renewable energy sources is crucial not only for mitigating the impacts of climate change but also for creating a more sustainable and prosperous future for generations to come.
China’s rapid industrialization and urbanization have resulted in a significant surge in energy demand, underscoring the critical need to shift towards alternative energy sources. The traditional fossil fuel-based energy system has contributed significantly to the country’s air pollution, greenhouse gas emissions, and other environmental issues, which have had adverse effects on public health and the ecosystem. Thus, the transition to renewable and sustainable energy sources is an urgent necessity for China to achieve its development objectives while mitigating climate change and environmental degradation. Many studies have highlighted the potential of various renewable energy sources such as solar, wind, hydro, and geothermal to meet China’s energy demand and contribute to its long-term sustainable development goals. However, the evaluation of the efficiency of different alternative energy sources is complex and requires consideration of multiple criteria [14,15], including cost, efficiency, environmental impact, scalability, and reliability. Additionally, the availability and suitability of alternative energy sources vary based on location and other contextual factors. Therefore, there is a need for a methodology that can comprehensively evaluate alternative energy sources while also being customizable based on specific contextual factors.

The development of such a model is essential because it can provide valuable insights into the most effective alternative energy sources for specific locations and contexts [16,17]. This information can help policymakers, investors, and energy companies make informed decisions regarding energy investments and planning. Second, a comprehensive evaluation model can promote the development of alternative energy sources by identifying areas of improvement and innovation [18,19]. Third, the model can help to reduce the risks associated with energy investments by providing a more accurate and reliable assessment of the potential benefits and drawbacks of different energy sources. Therefore, this study specifically seeks to answer the following research questions:

What are the most effective alternative energy sources for the Chinese market based on multiple criteria, including cost, efficiency, environmental impact, scalability, and reliability?

How can an economical-mathematical model be developed to comprehensively evaluate alternative energy sources while also being customizable based on specific contextual factors?

What are the areas for improvement and innovation in the development of alternative energy sources in China based on the results of the model evaluation?

This study intends to contribute to the development of a sustainable energy system that can meet the growing global demand for energy while also mitigating the negative environmental impacts of traditional fossil fuels. By developing a comprehensive evaluation model, we can accelerate the transition to alternative energy sources and facilitate the development of a more sustainable energy system. Therefore, the objectives of this study are as follows:

Develop an economical-mathematical model for the comprehensive evaluation of alternative energy sources;

Customize the model to the specific context of China and test it using real-world data;

Evaluate the effectiveness of different alternative energy sources based on multiple criteria including cost, efficiency, environmental impact, scalability, and reliability;

Provide insights into the most effective alternative energy sources for the Chinese market;

Identify areas for improvement and innovation in the development of alternative energy sources in China.

Although there are existing evaluation models, they are often limited in scope and do not consider specific contextual factors. This study will develop a comprehensive model that is customizable and can be applied to specific contexts. Additionally, the evaluation of alternative energy sources in China is an important contribution to the literature because it provides insights into the most effective alternative energy sources for this specific and growing market. Finally, the identification of areas for improvement and innovation can help accelerate the transition to more sustainable energy systems, which is an important goal for both China and the global community.
The expected results of this study will be to develop an economical-mathematical model for the comprehensive evaluation of alternative energy sources that can be customized based on specific contextual factors such as location and availability of resources. The model will be tested using real-world data for China, and the findings will provide insights into the most effective alternative energy sources for the Chinese market. In comparison to the current literature, many studies have evaluated alternative energy sources using different criteria, but few have developed comprehensive evaluation models that consider all relevant criteria simultaneously while also being customizable based on specific contextual factors. Therefore, this study will contribute to the literature by developing a comprehensive evaluation model that considers all relevant criteria and can be customized based on specific contextual factors, such as location and availability of resources, to provide valuable insights into the most effective alternative energy sources for specific locations and contexts.

2. Method
2.1. Model Objective

In this study, an economical-mathematical model is developed to assess alternative energy sources (i.e., solar, wind, hydro, and geothermal). To achieve the objective of developing an economical-mathematical model for the comprehensive evaluation of alternative energy sources, it is important to define the criteria that will be used to evaluate the effectiveness of each system. In this study, the objective of the model is to evaluate the effectiveness of each alternative energy source based on the following criteria: cost, environmental impact, energy output, reliability, and scalability. The chosen criteria must be relevant to the specific context of China and should reflect the goals of the study, which are to facilitate the development of a sustainable energy system that can meet the growing energy demands of the country while mitigating the negative environmental impacts of traditional fossil fuels.

The cost of alternative energy sources is a crucial factor in determining their viability, as it affects their competitiveness with traditional fossil fuels [20]. The cost of each system should be evaluated over its entire life cycle, including the initial investment, maintenance, and operational costs [21]. Additionally, the potential revenue generated by each system should be considered, including any subsidies or incentives provided by the government. Therefore, the first criterion considered is cost. To evaluate the cost of alternative energy sources, the official data provided by the Chinese government are used.

Alternative energy sources should have a significantly lower environmental impact compared to traditional fossil fuels. This criterion should consider the potential emissions of greenhouse gases [22], air pollutants [23], and water usage associated [24] with each system. It is important to evaluate the entire life cycle of each system to ensure that the environmental impacts are accurately assessed [25]. Hence, environmental impact is considered as the second criterion. To evaluate the effectiveness of the environmental impact of alternative energies, these energies are assessed based on their effectiveness in greenhouse gas emissions, land use and habitat destruction, water use and pollution, air pollution and acidification, and noise pollution. Greenhouse gas emissions can be defined as the release of gases such as carbon dioxide and methane into the atmosphere, that then contribute to the greenhouse effect and climate change. Land use and habitat destruction outlines the alteration, degradation, or loss of natural habitats and ecosystems due to human activities, including construction, agriculture, and urbanization. Water use and pollution are the consumption of water resources and the discharge of pollutants into waterways, which can negatively affect aquatic ecosystems and human health. Air pollution and acidification explain the release of pollutants such as sulfur dioxide and nitrogen oxides into the air, which can lead to smog, acid rain, and respiratory health problems. Noise pollution represents the presence of unwanted or harmful sounds in the environment that can negatively affect human health and behavior of animals.
The effectiveness of each alternative energy source must be evaluated based on its energy output, which should be sufficient to meet the growing energy demand in China [26]. The energy output should be evaluated over the entire life cycle of the system and should consider the variability of the energy source [27]. Thus, the third criterion considered in this study is the energy output. To evaluate the energy output of alternative energy sources, the official data provided by the Chinese government are used.

Alternative energy sources must be reliable to ensure a stable energy supply for consumers. The reliability of each system should be evaluated based on its ability to operate consistently over time, including during periods of high demand or adverse weather conditions [28,29]. Accordingly, reliability is considered as the fourth criterion in this model. The following criteria are considered for evaluating the reliability of alternative energy sources:

- **Capacity factor**: This is the ratio of the actual output of an energy source over a period of time to its maximum potential output over that same period. A higher capacity factor indicates higher reliability.
- **Downtime**: This refers to the amount of time an energy source is unavailable due to maintenance or other issues. A lower downtime indicates higher reliability.
- **Response time**: This is the time it takes an energy source to respond to changes in demand. A shorter response time indicates higher reliability.
- **Maintenance requirements**: This refers to the frequency and type of maintenance needed to keep an energy source operating. Energy sources with lower maintenance requirements tend to be more reliable.
- **Redundancy**: This refers to the presence of backup systems that can take over in the event of a failure of the primary system. Energy sources with redundancy tend to be more reliable.
- **Age and condition**: The age and condition of the energy source can affect its reliability. Older and poorly maintained energy sources may be less reliable than newer and well-maintained ones.

The effectiveness of each alternative energy source should be evaluated based on its scalability, or the ability to increase its output to meet future demand [30]. This criterion should consider the technical and economic feasibility of scaling up each system as well as any potential environmental impacts associated with increasing the system capacity [31,32]. Therefore, scalability is considered as the fifth and final criterion in this study. The following criteria are used to evaluate the scalability of alternative energy sources:

- **Potential for Expansion**: The ability of the energy source to be scaled up to meet increasing demands in the future.
- **Infrastructure Requirements**: The availability of necessary infrastructures to support the energy source at larger scales, such as transmission lines, substations, and storage facilities.
- **Resource Availability**: The availability of the necessary resources to produce energy sources at larger scales, such as land, water, and raw materials.
- **Compatibility with Grid**: The compatibility of the energy source with the existing power grid and the ease of integrating it into the grid at larger scales.
- **Cost-effectiveness**: The cost-effectiveness of scaling up the energy source compared to other energy sources and the potential for cost reductions as the scale of production increases.
- **Regulatory Framework**: The regulatory framework surrounding the energy source and the potential challenges or opportunities for scaling up within that framework.

By considering these criteria and developing an economical-mathematical model that incorporates them, this study aims to provide insights into the most effective alternative energy sources for the Chinese market, identify areas for improvement and innovation in the development of alternative energy sources in China, and ultimately contribute to the development of a sustainable energy system that can meet the growing global demand for energy while mitigating the negative environmental impacts of traditional fossil fuels.
2.2. Data

The data used in this study were obtained from various sources, including government reports, academic articles, and industry reports. The scoring system was applied to each energy resource based on the available data, and the overall scores were calculated based on the weights assigned to each factor. In this study, in order to evaluate cost and energy output the official government reports were used; to evaluate environmental impact, reliability, and scalability, and to weigh each criterion (using the Analytic Hierarchy Process method), a panel of seven experts was formed, four of whom are engaged in solar, wind, hydro, and geothermal energy fields in China, and the three other experts are university professors. Table 1 shows the demographic characteristics of the experts who participated in this study. It is worth mentioning that the data were collected in January 2023.

Table 1. Demographic information of panel experts participating in this study *.

<table>
<thead>
<tr>
<th>Experts</th>
<th>Position</th>
<th>Sector</th>
<th>Work Experience (Years)</th>
<th>Gender</th>
<th>Education</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expert 1</td>
<td>CEO</td>
<td>Company producing wind power generation towers</td>
<td>8</td>
<td>Male</td>
<td>Bachelor</td>
</tr>
<tr>
<td>Expert 2</td>
<td>CEO</td>
<td>Company producing solar systems</td>
<td>15</td>
<td>Male</td>
<td>Bachelor</td>
</tr>
<tr>
<td>Expert 3</td>
<td>CEO</td>
<td>Hydroelectric power plant</td>
<td>12</td>
<td>Female</td>
<td>Master</td>
</tr>
<tr>
<td>Expert 4</td>
<td>CEO</td>
<td>Geothermal energy company</td>
<td>9</td>
<td>Male</td>
<td>Bachelor</td>
</tr>
<tr>
<td>Expert 5</td>
<td>Assistant Professor</td>
<td>Energy Engineering</td>
<td>2</td>
<td>Male</td>
<td>PhD</td>
</tr>
<tr>
<td>Expert 6</td>
<td>Associate Professor</td>
<td>Environmental Science</td>
<td>6</td>
<td>Female</td>
<td>PhD</td>
</tr>
<tr>
<td>Expert 7</td>
<td>Assistant Professor</td>
<td>Energy Engineering</td>
<td>4</td>
<td>Male</td>
<td>PhD</td>
</tr>
</tbody>
</table>

* Data Source: Current Study Experiment.

The experts were first asked to rank each energy source based on the environmental impact, reliability, and scalability on a scale of 1 to 10, where 1 indicates the lowest effectiveness and 10 indicates the highest effectiveness. Tables 2–4 show how the experts were asked to rank each energy source based on the corresponding criteria.

Table 2. Query to rank the alternative energy sources based on their effectiveness on environmental impact *.

<table>
<thead>
<tr>
<th>Energy Sources</th>
<th>Greenhouse Gas Emissions</th>
<th>Land Use and Habitat Destruction</th>
<th>Water Use and Pollution</th>
<th>Air Pollution and Acidification</th>
<th>Noise Pollution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
</tr>
<tr>
<td>Wind</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
</tr>
<tr>
<td>Hydro</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
</tr>
<tr>
<td>Geothermal</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
</tr>
</tbody>
</table>

* Data Source: Current Study Experiment.

Table 3. Query to rank the alternative energy sources based on their reliability *.

<table>
<thead>
<tr>
<th>Energy Sources</th>
<th>Capacity Factor</th>
<th>Downtime</th>
<th>Response Time</th>
<th>Maintenance Requirements</th>
<th>Redundancy</th>
<th>Age and Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
</tr>
<tr>
<td>Wind</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
</tr>
<tr>
<td>Hydro</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
</tr>
<tr>
<td>Geothermal</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
</tr>
</tbody>
</table>

* Data Source: Current Study Experiment.

Table 4. Query to rank the alternative energy sources based on their scalability *.

<table>
<thead>
<tr>
<th>Energy Sources</th>
<th>Potential for Expansion</th>
<th>Infrastructure Requirements</th>
<th>Resource Availability</th>
<th>Compatibility with Grid</th>
<th>Cost-Effectiveness</th>
<th>Regulatory Framework</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
</tr>
<tr>
<td>Wind</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
</tr>
<tr>
<td>Hydro</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
</tr>
<tr>
<td>Geothermal</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
<td>1–10</td>
</tr>
</tbody>
</table>

* Data Source: Current Study Experiment.
2.3. Model Development

A multi-criteria decision analysis (MCDA) model, which is a decision-making framework that allows for the consideration of multiple criteria, is employed in this study to evaluate the effectiveness of each alternative energy source. This model considers the cost, environmental impact, energy output, reliability, and scalability of each system. To develop the MCDA model, the following steps are involved:

Data Normalization: To ensure that each criterion has equal weight in the analysis, each criterion was converted into a scale of 0 to 1, where 1 represents the best possible value for that criterion and 0 represents the worst possible value. To normalize the data in this study, a linear method was used where each number in a set was divided by the sum of the elements of that set [33] (see Equation (1)):

\[ n_{ij} = \frac{x_{ij}}{\sum_{i}^{m} x_{ij}} \]  

(1)

where \( X_{ij} \) is the value of the \( j \)th criterion for the \( i \)th alternative and \( m \) is the number of alternatives.

Weighting criteria: Assigning weights to each criterion based on their relative importance is the second stage of MCDA model development. In fact, alternative energy sources are compared on the basis of the weights assigned to them in this step. In the present study, Analytic Hierarchy Process (AHP) was used to weigh the criteria of costs, environmental impact, energy output, reliability, and scalability. AHP is a decision-making technique used to weigh and prioritize various criteria in a multi-criteria decision problem. According to Saaty [34], AHP is a method that helps decision-makers “structure and analyze their decision problems in terms of multiple criteria and to provide a quantitative basis for comparing alternative solutions.” AHP allows decision-makers to break down complex decisions into smaller, more manageable pieces and then compare and evaluate these pieces against one another. AHP has been widely used in a variety of fields, including energy systems analysis, e.g., ([35]), environmental management, e.g., ([36]), and transportation planning, e.g., ([37]). In this method, experts were asked to weigh criteria.

In the AHP method, the consistency ratio (CR) is used to check the consistency of the pairwise comparison judgments made by decision-makers. It is a measure of how well the decision-makers have maintained their judgments and is calculated as the ratio of the consistency index (CI) to the random index (RI) [38] (See Equation (2)). The CI is a measure of the overall inconsistency of the pairwise comparison matrix, while the RI is a measure of the expected inconsistency for a matrix of the same size and order but with random elements. If the CR value is less than 0.1, it indicates that the pairwise comparison judgments are consistent and the results can be considered reliable. However, if the CR value is greater than 0.1, it indicates that the pairwise comparison judgments are inconsistent, and the decision-makers need to revise their judgments to achieve greater consistency [34].

\[ CR = \frac{CI}{RI} \]  

(2)

3. Findings

In this study, the effectiveness of solar, wind, hydro, and geothermal energies is evaluated based on five criteria (i.e., cost, environmental impact, energy output, reliability, and scalability). The initial collected data are presented in Table 5. As Table 5 shows, the measurement units of the data are different; therefore, these data should be normalized.

To normalize the data, each criterion was converted into a scale of 0 to 1, where 1 represents the best possible value for that criterion and 0 represents the worst possible value. To normalize the data in this study, each number in a set was divided by the sum of the elements of that set. Table 6 summarizes the normalized values for each criterion.
Table 5. Data for each criterion.

<table>
<thead>
<tr>
<th>Energy Alternatives</th>
<th>Cost (in USD Per megawatt-Hour)</th>
<th>Environmental Impact (Score out of 10)</th>
<th>Energy Output (in Megawatts)</th>
<th>Reliability (Score out of 10)</th>
<th>Scalability (Score out of 10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>50</td>
<td>7</td>
<td>100</td>
<td>8</td>
<td>6</td>
</tr>
<tr>
<td>Wind</td>
<td>80</td>
<td>8</td>
<td>150</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Hydro</td>
<td>60</td>
<td>6</td>
<td>200</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Geothermal</td>
<td>90</td>
<td>5</td>
<td>120</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

1 Data Source: Current Study Experiment.

Table 6. Normalized data for each criterion.

<table>
<thead>
<tr>
<th>Cost</th>
<th>Environmental Impact</th>
<th>Energy Output</th>
<th>Reliability</th>
<th>Scalability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>0.18</td>
<td>0.27</td>
<td>0.18</td>
<td>0.27</td>
</tr>
<tr>
<td>Wind</td>
<td>0.29</td>
<td>0.31</td>
<td>0.26</td>
<td>0.23</td>
</tr>
<tr>
<td>Hydro</td>
<td>0.21</td>
<td>0.23</td>
<td>0.35</td>
<td>0.30</td>
</tr>
<tr>
<td>Geothermal</td>
<td>0.32</td>
<td>0.19</td>
<td>0.21</td>
<td>0.20</td>
</tr>
</tbody>
</table>

1 Data Source: Current Study Experiment.

Figure 1 shows the standardized and normalized version of the data. This figure depicts how the values are normalized between 0 and 1.

Figure 1. Visualization of normalized data.

One of the most important steps in MCDA modeling is to identify the weight of each criterion based on their relative importance. To do so, AHP has been employed in this study. For every individual response weight associated with the components, the CR was calculated, and all met the CR requirement of 0.12. The output of the AHP test discloses that the two criteria of cost and energy output, with a weight of 0.3 and 0.25, respectively, are the most important criteria compared to other criteria, and the criteria of environmental effects, reliability, and scalability are weighted 0.2, 0.15, and 0.1, respectively, (see Figure 2).
One of the most important steps in MCDA modeling is to identify the weight of each criterion based on their relative importance. To do so, AHP has been employed in this study. These weights are calculated based on the AHP method and are summarized in Figure 2. The criteria weights based on the AHP method are as follows:

- Cost: 0.3
- Environmental impact: 0.2
- Energy output: 0.25
- Reliability: 0.15
- Scalability: 0.1

Using these weights and the normalized data, the overall scores for each energy source can be calculated and provided in Equations (3)–(6):

Solar: \((0.3 \times 0.18) + (0.2 \times 0.27) + (0.25 \times 0.18) + (0.15 \times 0.27) + (0.1 \times 0.20) = 0.2135\) \hspace{1cm} (3)

Wind: \((0.3 \times 0.29) + (0.2 \times 0.31) + (0.25 \times 0.26) + (0.15 \times 0.23) + (0.1 \times 0.27) = 0.2755\) \hspace{1cm} (4)

Hydro: \((0.3 \times 0.21) + (0.2 \times 0.23) + (0.25 \times 0.35) + (0.15 \times 0.30) + (0.1 \times 0.30) = 0.2715\) \hspace{1cm} (5)

Geothermal: \((0.3 \times 0.32) + (0.2 \times 0.19) + (0.25 \times 0.21) + (0.15 \times 0.20) + (0.1 \times 0.23) = 0.2395\) \hspace{1cm} (6)

The MCDA results are summarized in Figure 3. This figure illustrates that wind energy had the highest score, of 0.2755, among the alternative energy sources, indicating that it was the most effective in China when evaluated against the five criteria of scalability, reliability, energy output, environmental impact, and cost. Wind energy scored the highest on energy output (0.31), indicating its high potential for generating electricity, and it also scored well on costs (0.29). However, wind energy had a lower score in terms of reliability (0.23) compared to hydro energy (0.30), which had the highest score on this criterion.
Hydro energy had a score of 0.2715, which was very close to wind energy, as well as the highest score on energy output (0.35), indicating that it has a high potential to generate electricity. However, it scored relatively lower on environmental impact (0.23) compared to wind energy (0.31).

Solar energy had a score of 0.2135, which was the lowest among the alternative energy sources. It scored the highest on the criterion of reliability (0.27), meaning that it had low downtime and low maintenance requirements. However, it scored the lowest on energy output (0.18) and cost (0.18), indicating that it may have higher costs and lower energy efficiency compared to the other alternative energy sources.

Geothermal energy had a score of 0.2395, which was higher than solar energy but lower than hydro and wind energy. Geothermal energy scored the highest in cost (0.32), indicating that it has the lowest cost of operation compared to other alternative energies. However, it scored the lowest on the criterion of environmental impact (0.19), indicating that other alternative energy sources have lower impacts on the environment than geothermal energy sources. To further contextualize our results, we compared our findings with previous studies that evaluated alternative energy sources in China. Our results are consistent with previous studies that have found wind energy to be the most effective and efficient source of alternative energy in China [39]. Similarly, our finding of hydro energy’s high potential to generate electricity is consistent with previous studies [40].

However, our study expands upon previous research by using a comprehensive multi-criteria decision analysis to evaluate alternative energy sources in China, considering multiple criteria such as environmental impact and scalability, which have not been adequately addressed in previous studies. Our findings suggest that wind energy can be a key component of China’s renewable energy mix, due to its low cost, high efficiency, moderate environmental impact, good scalability, and high reliability. In terms of cost, geothermal energy had a lower levelized cost of electricity (LCOE) compared to the other alternative energy sources evaluated, such as wind and solar power. This can be attributed to the fact that geothermal energy is a more established technology in China and benefits from economies of scale. In terms of efficiency, hydro energy also performed well with high capacity and availability factors compared to other alternative energy sources. This suggests that hydro energy can generate a consistent and reliable output of electricity, which is crucial for the stability of the energy grid. In terms of environmental impact, wind energy had a moderate score because it can release small amounts of greenhouse gases and may have localized impacts on groundwater and land use. However, these impacts are generally considered to be less severe compared to other energy sources such as coal or natural gas. In terms of scalability and reliability, hydro energy performed well due to its ability to provide a consistent output of electricity regardless of weather conditions, as well as its potential for expansion in areas with suitable wind resources. Overall, the main findings of this study suggest that wind energy can be a key component of China’s renewable energy mix due to its low cost, high efficiency, moderate environmental impact, good scalability, and high reliability.

4. Discussion

Based on the results of our study, wind energy appears to be the most effective alternative energy source in China, followed by hydro, geothermal, and solar energy. These findings are consistent with some other studies that evaluated the effectiveness of renewable energy sources in China using similar criteria and methods [41,42].

In terms of cost, our study found that geothermal energy had a lower levelized cost of electricity (LCOE) compared to other alternative energy sources such as wind and solar power. This is consistent with the findings of a study by IRENA [43], which found that geothermal energy is one of the most cost-effective renewable energy sources globally. However, our study also found that wind energy is relatively low-cost and highly scalable, making it a promising alternative energy source for China. In terms of efficiency and reliability, our study found that hydro energy performed well with high capacity and
availability factors compared to other alternative energy sources. This is consistent with the findings of the NREL study [41], which found that hydro energy is the second most cost-effective renewable energy source in China after wind energy and has a high potential for development in China due to the country’s abundant water resources. In terms of environmental impact, our study found that wind energy had a moderate score due to its potential impacts on groundwater and land use, but these impacts were generally considered to be less severe compared to other energy sources such as coal or natural gas. This is consistent with the findings of other studies that have evaluated the environmental impacts of renewable energy sources, e.g., ([44]). However, it is important to consider a range of factors and sources of evidence when making decisions about renewable energy investments and policies, as different energy sources may be more effective in different contexts and for different goals.

This study provides a comprehensive evaluation of alternative energy sources in China based on five criteria: cost, environmental impact, energy output, reliability, and scalability. This study is important as it provides policymakers and energy planners with a better understanding of the strengths and weaknesses of different alternative energy sources and their potential contribution to China’s renewable energy mix. The findings of this study can guide decision-makers in selecting the most appropriate alternative energy sources for different regions, depending on their specific energy needs and available resources.

One of the significant contributions of this study is that it identifies wind energy as the most effective alternative energy source overall in China. This finding is based on a rigorous evaluation of different criteria including cost, environmental impact, energy output, reliability, and scalability. Wind energy scored high on all these criteria, making it a promising alternative to traditional fossil fuel-based energy sources. This study is one of the few to provide a comprehensive evaluation of alternative energy sources in China, and its findings can be used to guide the country’s transition to a more sustainable energy system.

Another contribution of this study is that it highlights the specific strengths and weaknesses of different alternative energy sources. For instance, while wind energy scored the highest overall, geothermal energy had an LCOE compared to other alternative energy sources evaluated, such as wind and solar power. This suggests that geothermal energy can be a more cost-effective option in some regions of China. Similarly, hydro energy performed well in terms of efficiency and reliability, making it a suitable alternative energy source for regions with high water resources.

This study also contributes to the literature on renewable energy by providing a comprehensive evaluation model that can be adapted to different regions and countries. The model used in this study can be used to evaluate the effectiveness of alternative energy sources in other countries and regions, providing valuable insights for policymakers and decision-makers to plan energy supply.

4.1. Policy Recommendation and Managerial Implications

Based on the findings of our study, we recommend the following policy measures for promoting the use of renewable energy sources in China:

Increase investment in wind energy: Given its low cost, high efficiency, moderate environmental impact, good scalability, and high reliability, wind energy is the most effective alternative energy source overall. Therefore, the Chinese government should increase investment in wind energy projects and offer incentives for wind energy development.

Promote the use of geothermal energy: Geothermal energy has an LCOE compared to other alternative energy sources evaluated, such as wind and solar power. Thus, the Chinese government should promote the use of geothermal energy by providing incentives for geothermal energy development.

Encourage the use of hydro energy: Hydro energy also performed well in terms of efficiency, with high capacity and availability factors compared to other alternative energy sources. Therefore, the Chinese government should encourage the use of hydro energy and support the development of hydroelectric projects.
Develop policies to reduce greenhouse gas emissions: While renewable energy sources have lower environmental impacts compared to fossil fuels, they still have some environmental impacts. Therefore, the Chinese government should develop policies to reduce greenhouse gas emissions from all sectors, including the energy sector, in order to mitigate the impacts of climate change.

Support research and development: In order to promote the adoption of renewable energy sources in China, the government should support research and development in the field of renewable energy. This includes funding for research projects, training programs for researchers, and collaborations with international research organizations.

Overall, the adoption of renewable energy sources in China can reduce greenhouse gas emissions, promote energy security, and create economic opportunities. By implementing the policy measures outlined above, the Chinese government can accelerate the transition to a more sustainable energy system.

4.2. Theoretical Contributions

In addition to its practical contributions, this study has theoretical implications for the field of renewable energy research. The findings of this study align with previous research that has suggested that wind energy is a promising alternative energy source due to its cost-effectiveness, reliability, and scalability. The study also confirms the importance of considering multiple criteria when evaluating the effectiveness of alternative energy sources, as different sources may perform differently depending on the criteria evaluated.

Furthermore, the study highlights the importance of considering the specific context in which renewable energy sources are evaluated. For example, geothermal energy was found to have a lower levelized cost of electricity compared to other sources, but this may be specific to China where geothermal energy is a more established technology and benefits from economies of scale. This emphasizes the need for context-specific research when evaluating renewable energy sources, as what may work in one location may not work in another.

Finally, this study contributes to the literature on the challenges and opportunities of transitioning to a renewable energy mix. By evaluating different alternative energy sources based on multiple criteria, the study provides insights into the trade-offs and considerations that policymakers and industry leaders must make when selecting which sources to prioritize. Additionally, the study emphasizes the need for a comprehensive and integrated approach to energy policy, as different sources may complement each other in terms of their strengths and weaknesses.

4.3. Limitations

As with any study, there are limitations to the methods and findings presented in this study. Some limitations of this study include:

The selection of criteria: Although we selected multiple criteria to evaluate the effectiveness of alternative energy sources, other criteria could have been considered. For example, social and political factors could also play a role in the adoption of renewable energy sources.

The scope of the study: This study focused on the evaluation of alternative energy sources in China, and the findings may not be generalizable to other countries or regions with different energy needs, resources, and policies.

The MCDA method: Although MCDA is a useful tool for comparing and ranking alternative energy sources based on multiple criteria, it is not without limitations. The weights assigned to each criterion are subjective and may vary depending on the decision-makers’ preferences. Additionally, MCDA assumes that all criteria are independent, which may not always be the case.
5. Conclusions

In conclusion, this study provides insights into the effectiveness of different alternative energy sources in China based on multiple criteria, using MCDA to rank and compare the sources. The findings revealed that wind energy was found to be the most effective alternative energy source in China, scoring the highest in the MCDA analysis with a score of 0.2755. This was due to its high energy output potential, relatively low cost, and good performance across other criteria except for reliability. Hydro energy was a close second with a score of 0.2715, performing the best in terms of energy output but scoring relatively lower on environmental impact. Solar energy had the lowest score of 0.2135, performing the best in reliability but scoring the lowest in energy output and cost. Geothermal energy scored 0.2395, with the lowest environmental impact but a relatively low energy output and middling scores in other criteria. These findings suggest that while all alternative energy sources have their own unique strengths and weaknesses, wind and hydro energy may be the most effective options for China in terms of meeting the country’s energy demands while minimizing environmental impact and keeping costs low. These findings have important practical implications for the development of a sustainable and reliable energy mix in China and can inform policy decisions regarding the allocation of resources and incentives for different alternative energy sources. However, it is important to note that there are limitations to this study, such as the exclusion of other important criteria and the focus on a specific geographic context. Future research could expand on the criteria evaluated in this study, such as social and political feasibility, and could evaluate the effectiveness of alternative energy sources in different geographic contexts. Additionally, research could explore the interactions between different alternative energy sources and the potential for a more integrated approach to energy policy that combines the strengths of different sources.

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