Evaluation of the Significant Renewable Energy Resources in Sultanate of Oman Using Analytical Hierarchy Process

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Abstract- The Sultanate of Oman is a fast growing region and is the fifth largest economy in the Gulf Cooperation Council (GCC) regions. The oil and gas sectors are the main promoters of Oman's economy. The reservoirs of natural resources are insufficient for the future needs. The electricity sector of Oman mostly depends on natural gas and diesel. Renewable energy has no major role in the country's energy supply despite having valuable wind, hydropower and solar resources. This paper recommends the use of the available renewable energy sources and exploits their potential to facilitate the Sultanate of Oman, to aid the future plans of Oman in implementing renewable energy by 2020. The objectives of this paper are achieved by carrying out literature review of the importance of the renewable energy sources according to the conditions of Oman, and by utilizing Analytical Hierarchy Process (AHP) functioning software Expert Choice and manual calculations to select the best renewable energy source according to the conditions of Oman and the decision-makers. It can be stated that Oman has untouched potential of Renewable Energy sources and Wind Energy is identified as the potential renewable energy source for Sultanate of Oman.

Keywords Renewable Energy, analytical hierarchy process, expert choice, solar energy, wind energy, multi criteria decision analysis.

1. Introduction

Many countries around the world face electricity shortages and excess usage of the natural resources and fossil fuels. With the increase in population, the consumption of electricity and other daily products also increase due to which the natural resources and fossil fuels are depleted further to satisfy the needs of the civilians[1]. Similarly the population of Oman is also increasing constantly and the demand in usage of electricity is also increasing. Al Hatmi and Tan [2] determined and deduced the electricity demand in Oman for Muscat Interconnected System (MIS) and Salalah region from 2012 - 2018, pointing out that an increasing trend is observed in MIS by 8% while in Salalah by 10%. Thus an increasing trend in the electricity demand is observed. Therefore the ever-increasing trend in the consumption of electricity can be tackled by introducing some alternative source to fulfill the quota of electricity and it is clear that the use of renewable energy source is the best available option.

Oman has huge potential and unexploited renewable energy sources. In Oman till today there is no history of tapping the renewable energy sources on a large scale despite having valuable reservoirs of renewable energy sources. The solar energy in Oman is known to be the highest in the world and the density of solar reservoirs are present widely in all regions of Oman [3]. Oman receives solar radiation ranging between 5500 – 6000 Wh/m^2/day in July and 2500 – 3000 Wh/m^2/day in the month of January [2]. Wind energy is also an auspicious energy source in the coastal and Southern parts of Oman [4]. Annual wind speed reaches 5.8 m/s in Thamrait and Qayroon Hyriti which are the high wind intensity areas of Oman [2]. The geothermal energy does not have any potential use in the country, according to Petroleum Development Oman the highest temperature is 174˚C in the Northern part of the Omani mountains [3]. Biomass energy sources are available mostly in the Northern parts in the form of wastewater and agriculture waste and in the Southern parts of Oman in the form of wastewater and animal dung [5].

The selection of the ideal renewable energy source for Oman can be conducted by the implementation of Multi Criteria Decision Analysis (MCDA). The MCDA is a powerful tool to solve and ease complex decisions by prioritization process. It further consists of Analytical Hierarchy Process (AHP) that decomposes the problem into a large system of framework by considering series of activities in order to select the best solution. It composes hieratical structure of objectives, criteria, sub criteria and alternatives [6]. The appropriate data for the calculation are attained from making pairwise comparisons which provide weights of importance to the criteria decision, if the decisions are not consistent further amendments are made to make them consistent. The AHP reflects the human way of thinking which makes the solution feasible [6]. It considers factors related to the economy, environment, social and political nature. It has attracted the interest of many researchers and it is used to make decisions in various fields like: AHP application in the evaluation and selection of an information system engineering projects [7], in the flexibility measurements of power system generation for real time applications [8], application of AHP to decide on the latest smartphone [9], the application of AHP to measure Earthquake disaster risk map in East Java, Indonesia [10], and evaluation of Renewable Energy sources at remote regions, Greece using multi criteria analysis [11].

This research paper intends to select an ideal renewable energy source for Sultanate of Oman with the assistance of AHP methodology. Since no studies on the same context are being carried out, therefore this research has a vibrant role to play by selecting the best renewable energy source for Oman. The renewable energy sources considered in this paper are Biomass Energy, Wave Energy, Solar Energy, Geothermal Energy, Hydropower and Wind Energy, amongst which an ideal renewable energy is selected. The factors related to the selection procedure consists of economic, safety, reliability, environmental impacts, installed capacity, estimated potential, efficiency and social acceptance. The selection of renewable energy source brings forward an ideal choice for the government to focus on alternative sources to generate electricity and it also promotes vision 2020 to generate 10% electricity by renewable energy sources [4].

2. Material and Methods

AHP was first developed by Thomas Saaty in 1970 to solve complex decisions using the principles of philosophy and mathematics. Following steps are developed by Saaty for the application of AHP [12]:

- Initially the goal of the complex problem is decided and the criteria selection that affects the selection of the goal is identified.
- The problem is structured in the form a structural hierarchy that consists of the goal followed by criteria, sub criteria and alternatives at the end.
- The next step is the prioritization process in which pairwise comparisons of all the criteria with respect to each other and each criterion's comparison with all the alternatives are made in (n x n) matrix. The ratings are given according to the Saaty's scale shown in Table 1 [13]:

Table 1. Saaty's Scale

AHP scale of importance for comparison pair	Numerical Rating	Reciprocal Rating
Extremely Important	9	1/9
Very strong to extremely	8	1/8
Very Strong Importance	7	1/7
Strongly to very Strong	6	1/6
Strong Importance	5	1/5
Moderately to Strong	4	¼
Moderate Importance	3	1/3
Equally to Moderate	2	½
Equal Importance	1	1

- The next step is the measurement of consistency in which the consistency is calculated by founding the principal eigenvalue λ_{max} of each matrix of order n using Eq. (1):

$$Aw = \lambda_{max}\, w \quad (1)$$

Where A is the vector with priorities values and w is the eigenvalues of the vector A, λ_{max} is the principal eigenvalue and will be close to n (size of the matrix) which can be greater than or equal to n. After that the consistency index (CI) is determined using Eq. (2), and the consistency ratio (CR) is calculated using Eq. (3):

$$CI = (\lambda_{max}-n)/(n-1) \quad (2)$$

$$CR = CI\, /\, RI \quad (3)$$

The values of RI can be determined by the Random Consistency Index table as shown in Table 2 [13]:

Table 1. Random consistency index

Size of Matrix (n)	1	2	3	4	5	6	7	8	9	10
Random Consistency Index (RI)	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

- The local priorities values in the hierarchy over all the alternatives are synthesize

3. Results and Discussion

3.1. Application of AHP and Model Development

The data to be taken under consideration consists of criteria Cost [14], Efficiency [15], Installed Capacity (IC) [17], Environmental Impacts (EI) [16], Estimated Potential (EP) [17], Reliability [18], Safety [14] and Social Acceptance (SA) [18]. These criteria are selected after referring to experts and carrying out a literature review. Numeric ratings are given to the comparison of each criterion with the others. The ratings are given by a number of experts from Oman, the experts includes decision makers, experts and professors from Middle East College, Caledonian College, Sultan Qaboos University, German University of Technology, Oman Environmental Societies (Be'ah) and Haya Water. The data used for the analysis of the results is the ratings attained from the experts after solving questionnaire related to the topic. The alternatives of renewable energy to be examined are Biomass Energy, Solar Energy, Wind Energy, Hydropower, Geothermal Energy and Wave Energy. Figure 1 shows the structural Hierarchy consisting of the Goal at the top, with the criteria below the goal and the alternatives at the end of the hierarchy are shown.

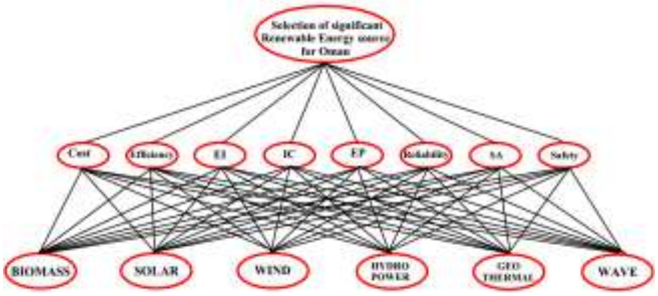
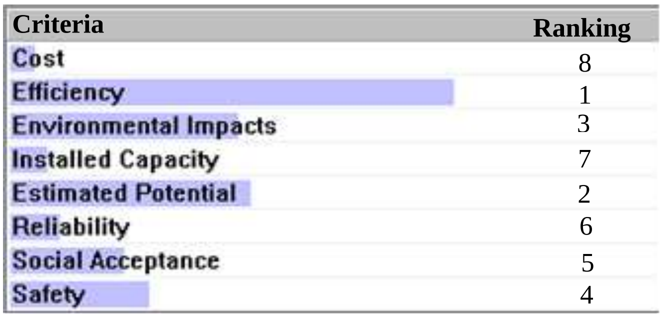


Fig. 1. Structural hierarchy for the selection of significant renewable energy source

The ratings for the criteria to criteria relation is entered in Expert Choice shown in Table 3. From the ratings it can be seen in Fig. 2 that Efficiency is the most preferred criterion amongst all. The values in Table 3 are the result of the expert's priority ratings while Expert Choice generated a visual graph Fig. 2 to visualize the ratings and ranking of each criterion. This prioritization model specifies that Efficiency, Estimated Potential, Environmental Impacts and safety are the top four prioritized criteria for the selection of the renewable energy source. The overall Consistency Ratio in Table 3 is 0.03 which is considered correct since it is under 0.09. The overall Efficiency of the power plant is considered the most important criteria and ranked more than all other criterion because if a renewable energy plant is being implemented, the most important factor to be considered is that how well this plant will perform and how efficiently it will overcome the power requirements and shortcomings. Estimated Potential is the measure of how well a particular plant is capable of fulfilling the power output required and how much potential it has, to produce efficiently. The third important criterion is Environmental Impacts, which also has huge importance because the environment shouldn't be affected by the implementation of any renewable energy source. It is also a measure of how much amount of harmful emissions is emitted from any renewable energy plant being brought forward for implementation.



Criteria	Ranking
Cost	8
Efficiency	1
Environmental Impacts	3
Installed Capacity	7
Estimated Potential	2
Reliability	6
Social Acceptance	5
Safety	4

Fig. 2. Rankings of criteria generated in expert choice

Table 2. Comparison of criteria to criteria

Selection of Renewable Energy	Cost	Efficiency	Environmental Impacts	Installed Capacity	Estimated Potential	Reliability	Social Acceptance	Safety
Cost	1	1/9	1/7	1	1/7	1/3	1/5	1/5
Efficiency	9	1	3	9	3	7	4	3
Environmental Impacts	7	1/3	1	7	1	3	3	2
Installed Capacity	1	1/9	1/7	1	1/7	1	1/3	1/5
Estimated Potential	7	1/3	1	7	1	5	3	2
Reliability	3	1/7	1/3	1	1/5	1	1/3	1/3
Social Acceptance	5	¼	1/3	3	1/3	3	1	1
Safety	5	1/3	½	5	1/2	3	1	1
Consistency Ratio = 0.03								

Referring to the priority ratings in Table 3, manual calculations are performed below. The ratings of Table 3 are entered in 8x8 matrix. Initially the entries in all rows of the matrix are multiplied with each other and then the n^{th} root of the product is taken. The value of n is 8 since it is 8x8 matrix. Eigenvector is the priority weight of each row of the matrix which is calculated by adding all the n^{th} root values of the concerned row, then dividing the sum with each individual n^{th} root value [17,18,19]. Calculation of the first row is shown below in Eq. (4):

$$\begin{bmatrix} 1 & 1/9 & 1/7 & 1 & 1/7 & 1/3 & 1/5 & 1/5 \\ 9 & 1 & 3 & 9 & 3 & 7 & 4 & 3 \\ 7 & 1/3 & 1 & 7 & 1 & 3 & 3 & 2 \\ 1 & 1/9 & 1/7 & 1 & 1/7 & 1 & 1/3 & 1/5 \\ 7 & 1/3 & 1 & 7 & 1 & 5 & 3 & 2 \\ 3 & 1/7 & 1/3 & 1 & 1/5 & 1 & 1/3 & 1/3 \\ 5 & 1/4 & 1/3 & 3 & 1/3 & 3 & 1 & 1 \\ 5 & 1/3 & 1/2 & 5 & 1/2 & 3 & 1 & 1 \end{bmatrix} \quad (4)$$

Now the ratings of the first row are multiplied with each other (1 x 1/9 x 1/7 x 1 x 1/7 x 1/3 x 1/5 x 1/5) whereas the product comes up as 3.023 x 10^{-5}. The 8th root value of the product (3.023 x 10^{-5}) is taken since the total elements are 8. The 8th root value for the first row (Cost) is 0.272. The sum of all the root product of the criteria comes up as 11.547 as shown in table 4 which further is divided by 0.272 to the get the first eigenvector. The same step is repeated to find the eigenvector values of all criteria respectively. The sum of all the eigenvector should be equal to 1 as shown in Table 4. If it exceeds 1 there must be some error in the calculation and the calculations need to be repeated [19].

Table 3. Manual PVE values

Criteria	Nth root product of the values	Eigenvector
Cost	0.272	0.024
Efficiency	3.966	0.343
Environmental Impacts	2.035	0.176
Installed Capacity	0.333	0.029
Estimated Potential	2.169	0.188
Reliability	0.487	0.042
Social Acceptance	1.028	0.089
Safety	1.257	0.109
Total	11.547	1.000

In Table 5 below the priority and eigenvector values of each criterion obtained from Table 4 is observed and compared with the eigenvector values obtained from Expert Choice.

Table 4. Shows the comparison of expert choice and manual PVE

Criteria	Expert Choice Eigenvector	Manual Eigenvector
Cost	0.024	0.024
Efficiency	0.348	0.343
Environmental Impacts	0.176	0.176
Installed Capacity	0.029	0.029
Estimated Potential	0.186	0.188
Reliability	0.043	0.042
Social Acceptance	0.089	0.089
Safety	0.107	0.109
Total	1.000	1.000

It can be seen in Table 5 that the eigenvector values of both cases are almost the same and the priority of the criterion is also same as the priority of the criterion in the Expert Choice. The manual priority can also be rated as Efficiency (34.3 %) followed by Estimated Potential (18.8 %), Environmental Impacts (17.6 %), Safety (10.9 %), Social Acceptance (8.9 %), Reliability (4.2 %), Installed Capacity (2.9 %) and the least rated priority is Cost (2.4 %). The next stage is to calculate λ_{max} which leads to the calculations of the Consistency Index and Consistency Ratio. The ratings from Eq. (4) are multiplied with the manual Eigenvector values (*Aw*) as given in Eq. (5).

$$\begin{bmatrix} 1 & 1/9 & 1/7 & 1 & 1/7 & 1/3 & 1/5 & 1/5 \\ 9 & 1 & 3 & 9 & 3 & 7 & 4 & 3 \\ 7 & 1/3 & 1 & 7 & 1 & 3 & 3 & 2 \\ 1 & 1/9 & 1/7 & 1 & 1/7 & 1 & 1/3 & 1/5 \\ 7 & 1/3 & 1 & 7 & 1 & 5 & 3 & 2 \\ 3 & 1/7 & 1/3 & 1 & 1/5 & 1 & 1/3 & 1/3 \\ 5 & 1/4 & 1/3 & 3 & 1/3 & 3 & 1 & 1 \\ 5 & 1/3 & 1/2 & 5 & 1/2 & 3 & 1 & 1 \end{bmatrix} \text{x} \begin{bmatrix} 0.024 \\ 0.343 \\ 0.176 \\ 0.029 \\ 0.188 \\ 0.042 \\ 0.089 \\ 0.109 \end{bmatrix} = \begin{bmatrix} 0.197 \\ 2.889 \\ 1.46 \\ 0.237 \\ 1.544 \\ 0.354 \\ 0.738 \\ 0.885 \end{bmatrix} \quad (5)$$

According to the theory of AHP method $Aw = \lambda_{max}\, w$, therefore λ_{max} can be determined by dividing each element of the product to the corresponding eigenvector values. This gives 0.197 / 0.024 = 8.21. The value of λ_{max} should not be less than the nth value which is 8. If they fall less than 8 there is an occurrence of error in the calculations [19]. The values of λ_{max} as given in Eq. 1 are as follows:

$$\begin{bmatrix} 0.197 \\ 2.889 \\ 1.46 \\ 0.237 \\ 1.544 \\ 0.354 \\ 0.738 \\ 0.885 \end{bmatrix} = \lambda_{max} \begin{bmatrix} 0.024 \\ 0.343 \\ 0.176 \\ 0.029 \\ 0.188 \\ 0.042 \\ 0.089 \\ 0.109 \end{bmatrix}$$

Therefore the values of λ_{max} as shown in Eq. (6) below are:

$$\begin{bmatrix} 8.21 \\ 8.42 \\ 8.3 \\ 8.17 \\ 8.21 \\ 8.43 \\ 8.3 \\ 8.12 \end{bmatrix} \text{Therefore, } \lambda_{max}\,(\text{avg}) = 8.27 \quad (6)$$

The λ_{max} value should not be less than *n* (8). It should be equal to or greater than the value of *n*. If the value is less than *n*, the calcinations need to be done again.

The Consistency Index can be found out by using Eq. (2):
CI = $(\lambda_{max}-n)/(n-1)$ = (8.27-8)/(8-1) = 0.0385

The consistency ratio can be found out by using Eq. (3) [17]:

$$\text{CR} = 0.0385/1.41 = 0.027$$

Where the value of RI is selected from Table 2 for n = 8. Since the CR (0.027) is less than 0.1 the calculations are considered consistent and the CR of the Expert Choice calculations are 0.03 which falls in accordance to the manual calculations. If the judgments were inconsistent, then the experts and decision makers need to revise the decisions until they are consistent. Table 6 shows the pairwise comparisons results of each criterion with respect to all the alternatives.

Table 6 shows the Priority Vector (PVE) of each criteria alternative comparison. The PVE values are attained from Expert Choice. However, Fig. 3 presents the ranking of renewable energy options based on the influence of all criteria.

Table 5. Priority of weights for criteria to alternative comparison

Alternatives /Criteria	Cost	Efficiency	EI	IC	EP	Reliability	SA	Safety
Biomass	0.423	0.188	0.326	0.046	0.128	0.102	0.047	0.056
Solar	0.042	0.061	0.083	0.363	0.568	0.364	0.437	0.355
Wind	0.042	0.449	0.059	0.190	0.070	0.343	0.239	0.355
Hydro power	0.188	0.159	0.129	0.309	0.128	0.102	0.118	0.156
Geothermal	0.101	0.080	0.282	0.046	0.052	0.046	0.041	0.034
Wave	0.205	0.062	0.121	0.046	0.055	0.042	0.118	0.045

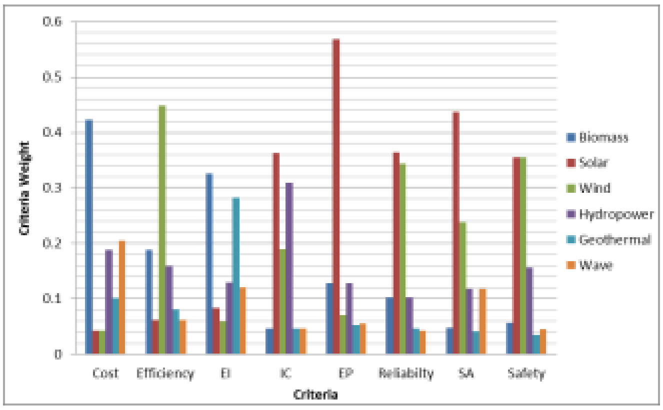


Fig. 3. Ranking of renewable energy alternatives considering all criteria

As presented earlier in Fig. 2, Efficiency was the most prioritized criterion and Wind Energy has the highest efficiency (0.449) amongst all the alternatives. Solar Energy has the highest Estimated Potential (0.568) and also widely accepted socially. Biomass is considered to have the highest Environmental impacts (0.326) along with geothermal energy. Solar and Wind energies are rated equally safe (0.355), Biomass energy is rated the most expensive renewable energy (0.423), considering maintenance and capital cost. Hydropower has the highest Installed capacity (0.309), since its installation requires large area to set up the plant. Solar energy is also considered the most reliable source of renewable energy followed by Wind energy. The decision makers and experts performed pairwise comparisons to develop relative importance of the variable present in the hierarchy. They performed a pairwise comparison of all the alternatives (renewable energy sources) with all the criteria. The pairwise comparison comforts to select the best alternative present in the lowest step of the hierarchy. The experts also have the consistency check which can figure out the inconsistent judgments which aids in rating the judgments accurately. Figure 3 further simplifies that wind energy and solar energy are the two most prioritized renewable energy sources. Wind energy is the most efficient source of energy as it has good ratings in the SA, Reliability and safety. While solar energy also has worthy prioritization ratings in the criteria IC, EP, Reliability and Safety. Secondly, both of these renewable energies don't affect the environment since they don't emit harmful gases unlike other renewable sources. Furthermore the Consistency Ratio of all the criteria to alternative comparison are acceptable and under the limit.

3.2. Synthesizing Judgments

The result synthesis includes priority ratings for the competing criteria as well as the overall priorities of the alternatives. By synthesizing the results, they are made mathematically sound because of the method, measurement and structuring used in Expert Choice [17]. The results are synthesized manually as well as by using Expert Choice. The result synthesis of this structure accomplished from Expert Choice is shown below in Fig. 4.

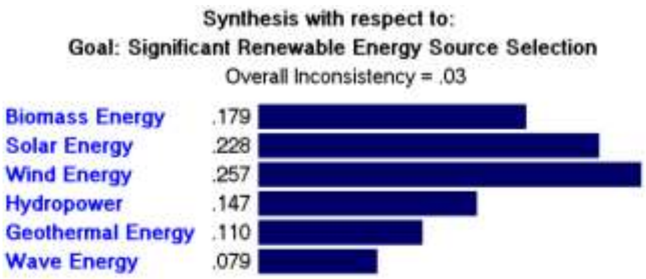


Fig. 4. Synthesis of results in expert choice

From the results obtained from Expert Choice, Wind Energy is recommended as the ideal source of Renewable Energy in Oman. It can be seen that wind Energy and Solar energy are the most preferred renewable energy sources in Sultanate of Oman. Wind energy is viewed as a valuable energy source that can mitigate climate [20] while, solar energy is considered as a promising technology for heating and cooling purposes[21]. Wind Energy is prioritized as the most promising renewable energy source as it dominates by (25.7 %) priority among all other alternatives followed by Solar Energy (22.8 %), Biomass Energy (17.9 %), Hydropower (14.7 %), Geothermal Energy (11 %) and the least prioritized Renewable energy is Wave Energy (7.9 %) according to the conditions of Oman. The overall inconsistency is 0.03 which is less than 0.1; therefore the results obtained are trustworthy, consistent and feasible.

The manual syntheses of results are as follows:

The PVE of all the criteria comparison with alternatives are determined initially and then multiplied with the eigenvector values of the criteria to criteria comparison calculated above. The product obtained shown below in Eq. (6) is the manual priority calculation of the alternatives [17,19].

$$\begin{bmatrix} 0.423 & 0.188 & 0.326 & 0.046 & 0.128 & 0.102 & 0.047 & 0.056 \\ 0.042 & 0.061 & 0.083 & 0.363 & 0.568 & 0.364 & 0.437 & 0.355 \\ 0.042 & 0.449 & 0.059 & 0.190 & 0.07 & 0.343 & 0.239 & 0.355 \\ 0.188 & 0.159 & 0.129 & 0.309 & 0.128 & 0.102 & 0.118 & 0.156 \\ 0.101 & 0.080 & 0.282 & 0.046 & 0.052 & 0.046 & 0.041 & 0.034 \\ 0.205 & 0.062 & 0.121 & 0.046 & 0.055 & 0.042 & 0.118 & 0.045 \end{bmatrix} \text{x} \begin{bmatrix} 0.024 \\ 0.343 \\ 0.176 \\ 0.029 \\ 0.188 \\ 0.042 \\ 0.089 \\ 0.109 \end{bmatrix} = \begin{bmatrix} 0.172 \\ 0.236 \\ 0.259 \\ 0.146 \\ 0.11 \\ 0.075 \end{bmatrix} \quad (6)$$

From the manual results it can be seen that the top priority renewable energy source is Wind Energy (25.9 %) followed by Solar Energy (23.6 %), Biomass Energy (17.2 %), Hydropower (14.6 %), Geothermal Energy (11 %) and Wave Energy (7.5%). It can be seen that both the results show consistency and comply with each other.

On the basis of the decision made by AHP process, it is necessary to determine the reservoirs and potential of wind and solar energy present in Oman. Based on several studies on the renewable energy sources in Oman Wind and Solar have shown technical feasibility and suitability to be used in Oman [2,3]. These both sources have the ability to produce electricity and to meet the power requirements.

4. Conclusion

Oman has unexploited reservoirs of renewable energy which can contribute to the country's electricity and power demands. Analytical Hierarchy Process methodology is adapted in this research to select an ideal renewable energy source for Sultanate of Oman. Wind Energy is identified as the ideal source of renewable energy for Oman with a PVE of (0.257). The highly rated criterion according to the experts is the efficiency of the Renewable Energy sources with a PVE of (0.343). Introducing renewable energy in Oman will not only diversify the economy and energy sources but also it will cope with the energy demands as per the objectives of Vision 2020. The level of solar energy density is among the highest densities in the world. Oman also recieves an ideal amount of wind speed in the areas of Thamrait and Qayroon Hyriti. According to the results of this research wind energy is prioritized over Solar energy in terms of overall effeciency. Solar energy is already being implemented in Oman in a lot of projects but due to bad maintenance propoerties it does not show the same effeicinecy propoerties as effecient wind energy has proved to be. Therefore, the results of this study completly falls in accordance to the conditions of Oman. Thus it is proved that both Wind and Solar Energy have huge potential as Renewable energy sources and will also help Oman establish an international position in the renewable energy sector and transmit onward the expansion of related technologies.

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