Process Integration and Optimization for Sustainability (2018) 2:61–71
https://doi.org/10.1007/s41660-017-0032-z

ORIGINAL RESEARCH PAPER

Selection of Optimum Renewable Energy Source for Energy Sector in Pakistan by Using MCDM Approach

Sarmad Ishfaq[1] · **Saad Ali**[2] · **Yousaf Ali**[3]

Received: 26 July 2017 / Revised: 7 December 2017 / Accepted: 19 December 2017 / Published online: 29 January 2018

Abstract

Power demands across the globe have been on rise for quite a time, and they will continue so in the years ahead. Most of the present day, energy requirements are met by non-renewable energy sources, i.e., burning fossil fuels which are not only expensive and polluting our environment but also depleting quite rapidly. A considerable portion of Pakistan import bills consists of petroleum products according to Pakistan Economic Survey 2015–2016. Renewable energy alternatives, i.e., wind, hydel, solar, and biomass, can be considered cheap, reliable, safe, and supply sustainable energy for the ever-increasing population. Renewable energy is getting more and more attention not only abroad but also in Pakistan as well. In order to decide the best renewable energy alternative for investment to meet rising energy demands of Pakistan, several factors such as economic, technological, and environmental have to be taken in consideration by the decision makers. Therefore, the paper discusses three important multiple criteria decision-making techniques, i.e., Analytical Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and the VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method in selection of the best renewable energy source that Pakistan should invest into. The results indicate that hydel power generation is the optimum source for meeting energy requirements followed by wind, biomass, and solar power-generating plants.

Keywords Environmental application · Renewable energy · MCDM · AHP · TOPSIS · VIKOR

Introduction

Energy is a basic necessity for human beings. Currently, the world's major energy supply comes from the combustion of fossil fuels (coal, hydrocarbon liquids, etc.). However, these resources not only produce harmful byproducts but are also due for depletion over the course of time even if the energy demand of world decreases. Therefore, research to develop renewable energy sources has seen a surge in recent years in order to mollify the consumption of energy and protect the environment (Mardani et al. 2015).

Renewable energy has been proven to be the solution for a sustainable, cost–effective, and environmentally friendly source of energy. It is the future of energy production and is capable of replacing fossil fuels in most of their applications. For this reason, renewable energy exploitation is gaining momentum in many countries across the world.

There are many different sources of renewable energy. The most popular among them which are being used for energy generation are as follows:

- Biomass refers to the biological material, dead or living, which can be used as a fuel.
- Hydel (most widely used form of renewable energy) is the production of energy through falling water under gravity.
- Solar power (one of the fastest growing energy sources) is the harnessing of sun's energy to produce electricity.
- Wind power is the production of energy by converting wind energy to some useful forms of energy with the help of wind turbines.

✉ Sarmad Ishfaq
sarmadishfaq94@gmail.com

Yousaf Ali
yousafkhan@giki.edu.pk

1 Faculty of Mechanical Engineering, Ghulam Ishaq Khan Institute of Engineering Sciences & Technology, Topi, Swabi, KPK, Pakistan

2 Ghulam Ishaq Khan Institute of Engineering Sciences & Technology, Topi, Swabi, KPK, Pakistan

3 Department of Management Science & Humanities, Ghulam Ishaq Khan Institute of Engineering Sciences & Technology, Topi, Swabi, KPK, Pakistan

Many studies have been conducted for the sustainability of the renewable energy resources. Selection of the most effective and efficient source involves different interacting factors. Traditional single criteria decision-making approaches cannot handle the complexity of this problem (San Cristóbal 2011). Therefore, for the renewable energy decision-making, we have to use multiple criteria decision-making (MCDM) techniques. MCDM methods deal with the process of making decisions in the presence of multiple objectives. A decision maker is required to choose among quantifiable or non-quantifiable and multiple criteria. Several methods have been developed to perform MCDM. Each method has its own characteristics, but they may be combined to give final result. Each methodology shares conflicting criteria, incommensurate units, and difficulty in selection of the alternative. Because of the conflicting criteria, the solution is highly dependent upon decision maker and it is a compromise. The conflicting aspects arise due to increasing complexity of social, technological, environmental, and economic factors (Afgan and Carvalho 2002).

This aim of this study is to use three different MCDM techniques namely VlseKriterijumska Optimizacija I Kompromisno Resenje (VIKOR), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Analytical Hierarchy Process (AHP) to select optimal renewable energy source for Pakistan to invest, in order to meet its energy demands. Detailed analysis and overview of each above mentioned methods is given in this study.

Literature Review

In recent times, many publications have been published regarding MCDM techniques also showing how it has evolved with time and its applications in various fields. Modern MCDM infrastructure was laid in 1950s and 1960s. Progress in MCDM research increased during the 1980s and early 1990s and continued its accelerated growth (Köksalan et al. 2011; Kabak and Dağdeviren 2014). Table 1 shows the past research conducted on various MCDM methods.

Over past years, a detailed study of MCDM techniques showed effectiveness in applying these techniques in areas of sustainability and renewable energy (Mardani et al. 2015). Table 2 shows the research contributions of various authors in field of environment and sustainability using MCDM methods.

MCDM techniques are also being employed for the energy sector of Pakistan. Table 3 shows the contribution of few authors.

Table 1 Past research carried out in field of MCDM

Author(s)	Research and contributions
Keeney et al. (1979)	The basics of decision with multiple objectives were formulated by Keeney, Raiffa, and Rajala
Saaty (1980)	A detailed report on the AHP was published by Saaty
Opricovic and Tzeng (2003)	Proposed new model based on VIKOR method and TOPSIS for defuzzification within the multiple criteria decision-making model with combined fuzzy criteria
Opricovic and Tzeng (2004)	Pointed out that TOPSIS presents the results with the largest distance from the negative ideal solution and shortest distance from the ideal solution but does not mention the importance of these distances
Tzeng et al. (2005)	Used VIKOR, AHP, and TOPSIS to point out the best fuel alternatives for busses
Opricovic (2007)	Applied and extended fuzzy VIKOR technique for solving problems in environmental issues
Ali et al. (2017a, b, c, d)	Used MCDM techniques for the selection of a fighter aircraft for the Pakistan Air Force to improve the effectiveness of air combat in war on terror
Chen and Wang (2009)	Presented a systematic and rational process to develop the optimal compromise solution and alternative under criteria selection by using VIKOR method and fuzzy set
Huang et al. (2009)	Developed a VIKOR model for MCDM which was used to determine the preference ranking from a set of alternatives in the presence of conflicting criteria
Opricovic (2009)	Opricovic applied the VIKOR technique for solving decision problems in water resource management
Liao and Xu (2013)	Liao and Xu analyzed the hesitant normalized Manhattan distance to incorporate the hesitant fuzzy circumstances by extending the VIKOR method
Ali et al. (2017a, b, c, d)	Used AHP and gamma test for the assessment of career selection problems in developing countries
Yousaf et al. (2017)	Used MCDM tools for production planning of Pakistan Tobacco Company (PTC)

Table 2 Use of MCDM techniques in environment and sustainability

Author(s)	Research and contributions
Shafiee and Kolios (2014)	Employed MCDM methods in order to minimize the operational risks of wind energy assets
Lozano-Minguez et al. (2011)	TOPSIS was employed by Lozano et al. for the selecting best support structure of an offshore wind turbine, among the three design options
Kolios et al. (2016)	Extended same concept used by Lozano et al. where an extended version of TOPSIS is introduced, which takes into consideration the stochasticity of inputs
Martin et al. (2013)	Presented a methodology to evaluate a number of floating support structure configurations, for offshore wind turbines deployed in deep waters
Doukas et al. (2010)	Used TOPSIS on energy policy objectives for sustainable development and renewable energy preferences
Datta et al. (2014)	Identified the best islanding detection method for a solar photovoltaic system by using TOPSIS along with other MCDM methods
Saelee et al. (2014)	Employed TOPSIS as the best tool for the selection of the best among three biomass types of boiler
Kahraman and Kaya (2010)	Implemented a fuzzy MCDM method, based on the AHP method, so as to find the optimum among energy policies in Turkey
Cobuloglu and Büyüktahtakın (2015)	Developed a new AHP-based methodology applicable to problems where uncertain data were available, and the criteria weights are identified from the MCDM case
San Cristóbal (2011)	Used VIKOR method for selecting a Renewable Energy project according to the Renewable Energy Plan of Spain. He combined AHP with VIKOR to provide weightage to different criteria according to its importance. The combination allows decision makers to assign the values based on their preferences.

Methodology and Analysis

The objective of this study is to find optimum source of renewable energy using VIKOR, TOPSIS, and AHP method. For this purpose, data from various sources were collected for four alternatives: hydel, solar, wind, and biomass energy. All alternatives were evaluated over six criteria discussed below:

1. Initial cost

   Initial costs are those which are incurred during the planning, design and construction phase of the project. It takes a huge amount of money to convert a raw renewable energy source to usable energy. Thus, it is one of the most important aspects when considering power generation dynamics. As for the scope of this paper, it is measured in million USD (mUSD).

2. Operations and maintenance (O&M) cost

   Equipment in the power producing plants is expensive, so it is uneconomical to replace it before its expected life. Therefore, it is important that the equipment is properly operated and maintained which costs capital. This capital, though not as much as initial cost, plays an important role when considering power generation dynamics. As for the scope of this paper, it is measured in million USD (mUSD).

Table 3 Use of MCDM techniques in energy sector of Pakistan

Author(s)	Research and contributions
Amer and Daim (2011)	Used MCDM for the first time for the energy sector of Pakistan. Presented AHP model for the selection and prioritization of various renewable energy technologies for electricity generation. Wind energy, solar photovoltaic, solar thermal, and biomass energy were used as alternatives.
Usmana et al. (2015)	Used AHP method for determining alternative energy resources at domestic level in Pakistan. A multiple criteria decision analysis approach was used to evaluate the entire present domestic alternative power system. Users' requirements were gathered through survey and were given weights using AHP.
Ali et al. (2017a, b, c, d)	Used AHP and other decision tools for the selection of suitable site in Pakistan for wind power plant installation
Ali et al. (2017a, b, c, d)	Used TOPSIS, AHP, and Pugh methods for the energy optimization in the wake of China Pakistan Economic Corridor (CPEC)

3. Power production capacity

   It is important to know how much power will be produced and added to the national grid by utilizing the raw renewable energy resources. It depends on amount of raw material available, auxiliary equipment, method of energy production, etc. As for the scope of this paper, it is measured in megawatts (MW).
4. Efficiency

   Efficiency of a power producing plant tells that how effectively the resources are being used to produce energy. It is one of the most important factors in power generations dynamics and thus considered in the analysis. As for the scope of this paper, it is measured in percentage (%).
5. Expected life

   Regardless of the resources used for producing energy (power), every power producing plant has a life expectancy. The expected life largely depends upon the raw resource used to produce energy, therefore, it is an important factor considered in this analysis. As for the scope of this paper, it is measured in years.
6. Environmental effects

   With a growing concern over harmful effects of gases and particulate matter released in the atmosphere by fossil fuel based energy sources, it is no doubt that this is the most important factor considered in this paper. The environmental effects considered here tell us that how many million tons of CO_2 can be avoided if we replace the non-renewable energy resources with renewable energy resources considered in this paper. As for the scope of this paper, it is measured in millions tons of CO_2 avoided per year (m tons CO_2 avoided/year).

The first two factors are categorized as economic, next two as technological, while the last one as environmental factor. Table 5 shows the data collected for each renewable energy alternative. The data is collected from various sources including Pakistan Energy Book (2014–2015), annual reports of the power plants in Pakistan, feasibility reports, letters of intent (LoI) of different future plants in Pakistan, newspapers, and other publicly disclosed information by Alternative Energy Development Board (AEDB) of Pakistan.

Assigning weights to criteria is a critical part of any MCDM study. In this paper we use aggregate criteria weights by utilizing empirical rank-weight relationship (Alfares and Duffuaa 2008) in which ordinal rankings of a number of criteria are converted into numerical weights. A linear relationship Eq. 1 specifies the average weight for each rank for an individual decision maker (DM), assuming a weight of 100% for the first-ranked (most important) factor (Alfares 2007). In this method, an m, number of DM's assign rank r to n, number of criteria, was based on individual DM's discretion. The individual ranks are then converted into individual weights for each criteria. After this, average weight for each criteria is calculated among all individuals (Alfares 2007). The following three steps are used to calculate the final weight of criteria which is mentioned in Table 4.

1. For each individual i, ranks $r_{i,j}$ are converted into individual weights $w_{i,j}$ for all n criteria by the following equation:

$$w_{i,j} = 100 – s_n\left(r_{i,j} – 1\right) \quad i = 1, \ldots, m, \quad j = 1, \ldots, n \tag{1}$$

   where $s_n = 3.19514 + \frac{37.75756}{n}$, for $1 \le n \le 21$, $1 \le r \le n$, and r and n are integers.
2. Average the weights obtained from all individuals m for all criteria to obtain aggregate weight $\overline{w_i}$ for all criteria.

$$w_i = \frac{1}{m} \sum_{i=1}^{m} w_{i,j} \quad j = 1, \ldots, n \tag{2}$$

3. Final weight w_{fi} for each criteria n is then calculated as

$$w_{fi} = \frac{\overline{w}_i}{\sum_{i=1}^{n} \overline{w}_n} \tag{3}$$

   where $i = 1, 2\ldots n$, $j = 1, 2\ldots n$.

Ranking is done for each criterion by researchers' discretion and engineering knowledge about power plants. The weights assigned are 0.2 for initial cost, 0.12 for O&M cost, 0.17 for capacity, 0.17 for efficiency, 0.13 for expected life,

Table 4 Calculation of weights by three DM's

Criteria	Initial cost	O&M cost	Capacity	Efficiency	Expected life	Env. effects
DM1 rank	3.00	6.00	4.00	2.00	5.00	1.00
DM2 rank	2.00	5.00	4.00	5.00	6.00	1.00
DM3 rank	1.00	6.00	3.00	4.00	5.00	2.00
DM1 weight	81.02	52.56	71.54	90.51	62.05	100.00
DM2 weight	90.51	62.05	71.54	62.05	52.56	100.00
DM3 weight	100.00	52.56	81.02	71.54	62.05	90.51
Avg. weight	90.51	55.72	74.70	74.70	58.89	96.84
Final weight	0.20	0.12	0.17	0.17	0.13	0.21

Table 5 Data for various renewable energy sources

	Initial cost (mUSD)	O&M cost (mUSD/year)	Capacity (MW)	Efficiency (%)	Expected life (years)	Environmental (m tons CO_2 avoided /year)
Biomass	1600	70	560	33	40	0.9
Hydel	39,412.737	788.25474	6790	80	100	24.25
Solar	570.2	57.02	1290	80	25	0.16
Wind	3650.326	6.69	1550	96.3	20	0.3

Source: Pakistan Energy Yearbook 2015, Hydrocarbon Development Institute of Pakistan https://www.hdip.com.pk/

and 0.21 for environmental effects. Environmental effects have highest aggregate weight as one of the main reasons to move towards renewable energy is to minimize or perhaps even eliminate the harmful effects of fossil fuel based energy on the environment. Initial cost has the second highest aggregate weight because in order to convert the raw resources of renewable energy to usable energy, a huge amount of capital is required. It is also important to know how much and how efficiently electricity is being produced; thus, a high weightage for capacity and efficiency is observed (Table 5). Also, all of the power-producing plant statistics (capacity, revenue, breakeven period, etc.) depend heavily on the overall efficiency of the plant. Capacity and efficiency are followed by expected life with second lowest weight and O&M cost with lowest weight because a much smaller amount of capital and effort is required for this as compared to others.

VIKOR Method

The VIKOR method was proposed by Opricovic and Tzeng in 2004 (Opricovic and Tzeng 2004). It is used to solve set of multiple criteria decision-making (MCDM) problems in which there are distinctive or conflicting units of criteria. The VIKOR method consists of an aggregating function that represents distance from the ideal solution. It takes the relative importance of all criteria into consideration as well as balance between total and individual satisfaction (San Cristóbal 2011). Compromise solution is the feasible solution based on "closeness to the ideal" concept. The compromise ranking is developed from the Lp-metric used as an aggregating function in a compromise programming method.

This method consists of following four steps (San Cristóbal 2011).

Step 1: Calculate best ideal value ideal value f_i^* and the worst ideal value f_i^- for all criteria.

where f_i^* = max fij if criteria represents a benefit and fi^* = min fij if criteria represents a loss and f_i^- = min fij if criteria represents a benefit, and f_i^- = max f_{ij} if criteria represents a loss and j represents the alternatives. Table 6 shows results of step 1.

Step 2: Calculate the value of S_j using Eq. 4 which is weighted and normalized Manhattan (taxi cab) distance and R_j using Eq. 5 which is weighted and normalized Chebyshev distance.

$$S_j = \sum_{i=1}^{n} \frac{w_{fi}\left(f_i^* - f_{ij}\right)}{\left(f_i^* - f_i^-\right)} \tag{4}$$

where w_{fi} represents weight of a criteria

$$R_{\mathrm{j}} = \max\, w_{fi} \frac{\left(f_i^* - f_{ij}\right)}{\left(f_i^* - f_i^-\right)} \tag{5}$$

where w_{fi} represents weight of a criteria and j = 1, 2…J

Step 3: Calculate the values of Q_j using Eq. 6 by relation

$$Q_{\mathrm{j}} = \frac{v\left(S_{\mathrm{j}} - S^*\right)}{\left(S^- - S^*\right)} + \frac{(1-v)\left(R_{\mathrm{j}} - R^*\right)}{\left(R^- - R^*\right)} \tag{6}$$

where S^* = min S_{j}, S^- = max S_{j} and R^* = min R_{j}, R^- = max R_{j}..

The solution obtained by min S_j is with a maximum group utility ("majority" rule), and the solution obtained by min R_j is with a minimum individual regret of the "opponent." Here v is the weight for the strategy of maximum group utility, and $1 - v$ is the weight of the individual regret. Although value of v varies between 0 and 1 based on decision maker (individual

Table 6 Best ideal value f_i^* and the worst ideal value f_i^- for all criteria are based on Table 5

	Cost (mUSD)	Maintenance cost (mUSD/year)	Capacity (MW)	Efficiency (%)	Expected life (years)	Environmental (m tons CO_2 avoided /year)
f_{i}^*	570.2	6.69	6790	96.3	100	24.25
f_{i}^-	39,412.737	788.25474	560	33	20	0.16

Table 7 Values of S, R, and Q with $v = 0.5$ in decreasing order

	S_j		R_j		$Q_{v=0.5}$
Biomass	0.65212021	Solar	0.21454865	Solar	0.7923229
Hydel	0.36660710	Hydel	0.20053441	Hydel	0
Solar	0.53353114	Wind	0.21330179	Biomass	0.76486288
Wind	0.49886658	Biomass	0.20795811	Wind	0.68713176

or group) choice, it is usually taken as 0.5 (San Cristóbal 2011).

Step 4: Rank all the alternatives by sorting Q, R, and S values in decreasing order as shown in Table 7. The compromise solution is decided as $A^{(1)}$ which is minimum value by Q ranking if following two conditions are fulfilled (Opricovic and Tzeng 2007).

a. Acceptable advantage
$Q\ [A^{(2)} - A^{(1)}] \geq DQ$, where $DQ = 1\ /\ (J - 1)$, $A^{(1)}$ and $A^{(2)}$ are the minimum and second minimum values in ranking by Q while J is the total number of alternatives.
b. Acceptable stability in the decision-making.
The minimum value of S or/and R ranking should also indicate the alternative $A^{(1)}$ to be the best solution.

It can be seen that both the abovementioned conditions (a and b) are true so hydel is the compromise solution by VIKOR method.

However, if one of the two conditions is not fulfilled, then a set of more than one compromise solutions are proposed.

c. Alternative $A^{(1)}$ and $A^{(2)}$ are both compromise solutions if only condition b is not fulfilled.
d. Alternative $A^{(1)}, A^{(2)}, \ldots A^{(M)}$ are all compromise solutions if condition a is not fulfilled. $A^{(M)}$ can be calculated by the equation $Q(A^{(M)} - A^{(1)}) < DQ$ for maximum value of M (position of mentioned alternatives are "in closeness").

In this case, however, both the conditions are satisfied, so there is only one compromise solution.

TOPSIS Method

TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is a multiple criteria decision analysis technique which was presented by Hwang and Yoon in 1981. The basic concept of this method is that the selected alternative should have the shortest distance from the positive ideal solution (PIS) or longest distance from the negative ideal solution (NIS) in geometrical sense. It assumes that criteria are monotonically (linearly) increasing or decreasing. It is a compensatory aggregation in to which certain weightage is assigned to each alternative according its importance and coherence with the required criterion. An evaluation matrix X_{mn} is created which composes of m number of alternatives (rows) and n number of criteria (columns). A preference is assigned to each criterion between 1 and 9 for every alternative as shown in Table 18. This preference is based on decision makers' (DM's) discretion and data collected. The matrix is then normalized (N_{ij}) using Eq. 7, and weighted decision matrix (W_{ij}) is formed by multiplying normalized matrix columns with respective weight of the criteria using Eq. 8. N_{ij} and W_{ij} are shown in Tables 19 and 20, respectively. Positive ideal solution P_i and negative ideal solution N_i are calculated for each criteria, such as "$P_i = \max(W_{ij})$" if it represents a benefit and "$P_i = \min(W_{ij})$" if it represents a loss. Similarly, "$N_i = \min(W_{ij})$" if it represents a benefit and "$N_i = \max(W_{ij})$" if it represents a loss. Table 8 gives the values P_i and N_i from weighted decision matrix based on data from Table 5.

$$N_{ij} = \frac{X_{ij}}{\sqrt{\sum_{i=1}^{m} \left(X_{ij}\right)^2}} \tag{7}$$

where $i = 1, 2\ldots4$ and $j = 1, 2\ldots6$

$$W_{ij} = N_{ij} \times W_j \tag{8}$$

where W_j represents weight of the criteria

Geometric distance between an alternative from the negative ideal solution S_i and positive ideal solution S_i* is calculated using Eqs. 11 and 12, respectively. This is followed by a separation measure S_n given by Eq. 9 which describes distance from negative ideal solution. Its value varies between 0 and 1 indicating worst alternative best alternative, respectively. It should be noted that separation measure can be used to measure distance from positive alternative using Eq. 10. In that case, best alternative will be the one with minimum value. The

Table 8 Positive ideal solution P_i and negative ideal solution N_i for each criteria

	Initial cost (mUSD)	O&M cost (mUSD/year)	Capacity (MW)	Efficiency (%)	Expected life (years)	Environmental (m tons CO_2 avoided/year)
P_i	0.070201086	0.043218278	0.108632174	0.09864384	0.09168719	0.150780915
N_i	0.126361955	0.0777929	0.036210725	0.076722987	0.030562397	0.050260305

Table 9 Geometric distance from positive ideal solution S_i*, negative ideal solution S_i', and separation measure S_n based on Table 8

	S_i*	S_i'	S_n
Biomass	0.089731539	0.090195942	0.501290528
Hydel	0.062716968	0.139227694	0.689434880
Solar	0.091706509	0.083803001	0.477484103
Wind	0.124542195	0.062441472	0.333940782

result in both the cases will be same. The result in both the cases will be same. The values of S_i', S_i*, and S_n are given the Table 9 in decreasing order and are based on Table 8.

$$S_n = S_i'/\left(S_i' + S_i^*\right) \tag{9}$$

$$S_n' = S_i^*/\left(S_i' + S_i^*\right) \tag{10}$$

$$S_i' = \sqrt{\sum_{j=1}^{n}\left(W_{ij}-N_j\right)^2} \tag{11}$$

$$S_i^* = \sqrt{\sum_{j=1}^{n}\left(W_{ij}-P_j\right)^2} \tag{12}$$

In Eqs. 11 and 12, i and n represent alternatives and criteria respectively while N_i and P_j represent negative ideal solution and positive ideal solution, respectively, for each criteria.

Since maximum S_n value is for hydel, it is the optimal alternative followed by biomass, solar, and wind energy.

AHP Method

The Analytic Hierarchy Process (AHP) introduced first by Prof. Thomas L. Saaty. It is a multiple criteria decision-making approach in which a complex problem is broken down into hierarchy with objective/goal at top level, criteria, and sub-criteria at mid-level while alternatives are placed at the bottom level of hierarchical process. Starting from the bottom, alternatives are compared with each other to find their relative importance with respect to each element in the above level (criteria or sub-criteria). The verbal terms of the Saaty's fundamental scale of 1–9 are used to assess the intensity of preference between two elements. The value of 1 indicates equal importance, 3 moderately more, 5 strongly more, and 7 very strongly, and 9 indicates extremely more importance. The values of 2, 4, 6, and 8 are allotted to indicate compromise values of importance (Pohekar and Ramachandran 2004). AHP methods takes into account the consistency ration (CR) which is ratio of inconsistency index (CI) to randomly generated index (RI) to assure the decision maker that his judgments were correct and final answer is consistent. It is calculated for each pairwise comparison matrix at each level, and its value should be less than 0.1. If it is not, then the pairwise comparison matrix needs to be re-evaluated. Method for checking consistency is discussed in detail in Saatys' original AHP paper (give ref. to AHP original paper)

In this case, the alternatives are compared with each other for initial cost, O&M cost, etc. Thus, we have six matrices denoted by M as shown in Table 14. The preference assigned to the alternatives is based on researchers' discretion; however, assigned preferences appeal common sense and are justified according to the data in Table 5. The value of preferences is iterated many times to reduce the consistency ratio (CR) below 0.1.

After this, a normalized matrix is formed by dividing column elements with the column sum for each criterion as shown in Table 15. An equation representing the normalized matrix can be written as

$$N_{ij} = \frac{Mij}{\sum_{i=1}^{j} Mij} \tag{13}$$

where i and j represent row and column of the each matrix, respectively.

Eigenvectors of each level are found by taking average of rows in normalized matrix for each criteria (total six eigenvectors). A matrix is created by combining all the eigenvectors obtained at a level shown in Table 10.

Then, same procedure is done for upper levels and a matrix of eigenvectors is formed at each level until there is only one eigenvector formed at criteria level. Since what we have are not considering any sub-criteria, we will have only one more upper level (criteria) and hence only one eigenvector after comparing the criteria with each other shown by pairwise comparison matrix. The pairwise comparison matrix of criteria is shown in Table 16, normalized comparison matrix of criteria is shown in Table 17, while eigenvector for criteria is shown in Table 11. Preference to criteria is given purely on the basis of weights of criteria. Equation 13 can also be used here to represent the normalized comparison matrix for

Table 10 Combined eigenvector matrix for alternatives

	Initial cost	O&M	Energy	Efficiency	Expected life	Environmental effects
Biomass	0.140	0.111	0.063	0.040	0.214	0.303
Hydel	0.492	0.706	0.629	0.211	0.638	0.537
Solar	0.051	0.119	0.116	0.199	0.092	0.054
Wind	0.317	0.064	0.192	0.550	0.056	0.106

Table 11 Eigenvector for criteria

Initial cost	0.235
O&M cost	0.031
Capacity	0.139
Efficiency	0.132
Expected life	0.041
Environmental	0.423

criteria. However, the matrices *M* and *N* will be replaced by M^c and N^c respectively where "c" denotes criteria.

Then, eigenvector matrices of two successive levels are multiplied with each other from the bottom until final composite vector of weight coefficients (weight of an alternative with respect to the goal) is obtained. In this case, eigenvector form criteria level as shown in Table 11 is multiplied with matrix of eigenvectors from alternatives level as shown in Table 10. Values in the final vector represent the importance of each alternative to the goal with highest value being the most important as shown in Table 12.

Table 12 shows hydel energy to be optimal solution as it has largest weight coefficient with respect to the goal. It is followed by wind, biomass, and solar energy.

Discussion

The study used three multi-criteria decision analysis tools, VIKOR, TOPSIS, and AHP, and all of them resulted in hydel being the optimal renewable source of energy as an alternative to the non-renewable sources currently used in Pakistan for energy production. The renewable energy sources were evaluated under six criteria including initial cost, operations and management cost, capacity, efficiency, expected life, and environment. By comparing the results of the three different techniques, it can be concluded that all the three tools settle for the same alternative to be the optimal one. However, TOPSIS and AHP show differences for other sources.

The results of this research relate to that of the study of Amer et al. in context of Pakistan (Amer and Daim 2011). However, the difference lies within the evaluated alternatives. Hydel was not considered to be evaluated by them so the optimal alternative by their research was biomass. This study ranks biomass as second best alternative by TOPSIS while third by AHP due to the consideration of hydel energy source.

Table 12 Ranking of alternatives in decreasing order by AHP

Biomass	0.186
Hydel	0.490
Solar	0.084
Wind	0.240

Table 13 Ranking results as calculated by VIKOR, TOPSIS, and AHP

	Ranking by VIKOR (single compromise solution)	Ranking by TOPSIS	Ranking by AHP
Biomass		2	3
Hydel	1	1	1
Solar		3	4
Wind		4	2

Among the criteria selected to evaluate the four renewable sources of energy in this study, high capacity, longer life expectancy, and minimum environmental damage acted positively for hydel thus making it the optimal choice of energy production despite of its high initial cost.

Conclusions and Recommendations

In this study, three MCDM methodologies, VIKOR, TOPSIS, and AHP, were used to determine the optimum source of renewable energy in Pakistan by evaluating them over mentioned six criteria. All three of them conclude that hydel energy is the optimal source of renewable energy for Pakistan to invest in order to meet its energy demands. Comparison of the results obtained by all three methods is shown in Table 13.

Pakistan has an abundance of natural hydel resources; therefore, Pakistan needs to gain maximum benefit by utilizing all its natural water supplies and construct small and large hydel energy projects in order decrease the supply demand gap, hence reducing energy crisis. The results also show biomass to be the second and third best alternative according to TOPSIS and AHP, respectively. There are too few projects of biomass working in Pakistan right now as compared to other alternatives. Since biomass energy generation greatly depends upon amount of raw material available (wood chips, crop wastes, etc.) and Pakistan is an agricultural country, a great deal of work can be done in this field. Wind energy, despite its high efficiency, is second and fourth according to AHP and TOPSIS results, respectively. This is justifiable as seen by its high initial cost and short-life expectancy. Also, production of wind energy greatly depends upon climate conditions such as humidity, wind speed, and air density which are not always reliable. However, if the wind corridors in Pakistan are utilized optimally, wind energy can add a considerable amount of energy in the national grid. Similarly, solar energy is ranked as fourth and third according to TOPSIS and AHP results, respectively. It is also justifiable as seen by its low power capacity/cost ratio as compared to other alternatives and its short-life expectancy. It is recommended to not to invest in this field as of yet; however, its potential may be utilized later in the future.

Appendix

Table 14 Pairwise comparison matrices of alternatives for all six criteria

	Biomass	Hydel	Solar	Wind		Biomass	Hydel	Solar	Wind
Pairwise comparison matrix for cost					Pairwise comparison matrix for O&M cost				
Biomass	1	1/3	3	1/3	Biomass	1	1/2	1	1/7
Hydel	3	1	9	2	Hydel	2	1	2	1/3
Solar	1/3	1/9	1	1/6	Solar	1	1/2	1	1/9
Wind	3	1/2	6	1	Wind	7	3	9	1
Pairwise comparison matrix for capacity					Pairwise comparison matrix for efficiency				
Biomass	1	1/9	1/7	1/3	Biomass	1	1/7	1/7	1/9
Hydel	9	1	5	4	Hydel	7	1	1	1/3
Solar	2	1/5	1	1/2	Solar	7	1	1	1/4
Wind	3	1/4	2	1	Wind	9	3	4	1
Pairwise comparison matrix for expected life					Pairwise comparison matrix for environment				
Biomass	1	1/4	3	4	Biomass	1	1/2	6	3
Hydel	4	1	7	9	Hydel	2	1	9	5
Solar	1/3	1/7	1	2	Solar	1/6	1/9	1	1/2
Wind	1/4	1/9	1/2	1	Wind	1/3	1/5	2	1

Table 15 Normalized pairwise comparison matrices of alternatives for all six criteria

	Biomass	Hydel	Solar	Wind		Biomass	Hydel	Solar	Wind
Normalized pairwise matrix for cost					Normalized matrix for O&M cost				
Biomass	0.136	0.171	0.158	0.095	Biomass	0.091	0.100	0.077	0.090
Hydel	0.409	0.514	0.474	0.571	Hydel	0.182	0.200	0.154	0.210
Solar	0.045	0.057	0.053	0.048	Solar	0.091	0.100	0.077	0.070
Wind	0.409	0.257	0.316	0.286	Wind	0.636	0.600	0.692	0.630
Normalized matrix for capacity					Normalized matrix for efficiency				
Biomass	0.091	0.100	0.077	0.090	Biomass	0.042	0.028	0.023	0.066
Hydel	0.182	0.200	0.154	0.210	Hydel	0.292	0.194	0.163	0.197
Solar	0.091	0.100	0.077	0.070	Solar	0.292	0.194	0.163	0.148
Wind	0.636	0.600	0.692	0.630	Wind	0.375	0.583	0.651	0.590
Normalized matrix for expected life					Normalized matrix for env. effects				
Biomass	0.179	0.166	0.261	0.250	Biomass	0.286	0.276	0.333	0.316
Hydel	0.716	0.665	0.609	0.563	Hydel	0.571	0.552	0.500	0.526
Solar	0.060	0.095	0.087	0.125	Solar	0.048	0.061	0.056	0.053
Wind	0.045	0.074	0.043	0.063	Wind	0.095	0.110	0.111	0.105

Table 16 Pairwise comparison matrix of criteria

Pairwise comparison matrix of criteria						
	Cost	O&M cost	Capacity	Efficiency	Expected life	Env. effects
Cost	1.00	5.00	2.00	3.00	5.00	2.00
O&M cost	0.20	1.00	0.33	0.50	1.00	0.33
Capacity	0.50	3.00	1.00	2.00	5.00	1.00
Efficiency	0.33	2.00	0.50	1.00	2.00	0.50
Expected life	0.20	1.00	0.20	0.50	1.00	0.33
Env. effects	0.50	3.00	1.00	2.00	3.00	1.00

Table 17 Normalized pairwise comparison matrix of criteria

Normalized pairwise comparison matrix of criteria						
	Cost	O&M cost	Capacity	Efficiency	Expected life	Env. effects
Cost	0.366	0.333	0.397	0.333	0.294	0.387
O&M cost	0.073	0.067	0.066	0.056	0.059	0.065
Capacity	0.183	0.200	0.199	0.222	0.294	0.194
Efficiency	0.122	0.133	0.099	0.111	0.118	0.097
Expected life	0.073	0.067	0.040	0.056	0.059	0.065
Env. effects	0.183	0.200	0.199	0.222	0.176	0.194

Table 18 Evaluation matrix (X_{mn}) of TOPSIS method

Evaluation matrix, X_{mn}						
	Initial cost	O&M cost	Capacity	Efficiency	Expected life	Env. effects
Biomass	7	5	3	7	7	7
Hydel	9	7	9	7	9	9
Solar	5	9	7	7	5	5
Wind	7	7	7	9	3	3

Table 19 Normalized matrix (N_{ij}) of TOPSIS method

Normalized matrix (N_{ij})						
	Initial cost	O&M cost	Capacity	Efficiency	Expected life	Env. effects
Biomass	0.4901	0.3501	0.2188	0.4636	0.5466	0.5466
Hydel	0.6301	0.4901	0.6564	0.4636	0.7028	0.7028
Solar	0.3501	0.6301	0.5105	0.4636	0.3904	0.3904
Wind	0.4901	0.4901	0.5105	0.5960	0.2343	0.2343

Table 20 shows weighted normalized matrix (W_{ij}) of TOPSIS method

Weighted normalized matrix (W_{ij})						
	Initial cost	O&M cost	Capacity	Efficiency	Expected life	Env. effects
Biomass	0.0983	0.0432	0.0362	0.0767	0.0713	0.1173
Hydel	0.1264	0.0605	0.1086	0.0767	0.0917	0.1508
Solar	0.0702	0.0778	0.0845	0.0767	0.0509	0.0838
Wind	0.0983	0.0605	0.0845	0.0986	0.0306	0.0503

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