A Hierarchy Grey Relational Analysis for Selecting the Renewable Electricity Generation Technologies

Ahmet Sarucan, M. Emin Baysal, Cengiz Kahraman, Orhan Engin

Abstract— **Energy resources are classified as renewable and non-renewable in general. Non renewable energy resources have been exhausted gradually. Renewable energy resources such as wind power, hydropower, geothermal power, solar power and photovoltaic power have importance more than ever before. But, researchers are looking for selections of renewable electricity generation as it is a technological problem. This problem is a multi-criteria decision making problem. One of the solution methods for this problem is a combination of the analytic hierarchy process (AHP) and the grey relational analysis (GRA). Hierarchical GRA method is based on grey system theory. In this study, a new approach to the selection of renewable electricity generation is prepared using multi-criteria decision making method. The hierarchical GRA frame work uses three criteria and sub-criteria from which it possible to evaluate to different renewable electricity generation technologies. This application is a novel approach for the selection of renewable electricity generation technologies.**

Index Terms— **Analytic Hierarchy Process, Grey Relation Analysis, Renewable Electricity Generation Technology**

I. INTRODUCTION

One of the main inputs of an economy is obviously energy. Amount of energy used by a country is a distinctive characteristic of its competition level. Social and environmental pressure, lack of energy resources pushes the governments and private sectors to produce more efficient and cleaner energy. Energy resources mainly divided into two parts as renewable and non-renewable according to depletion or cycling of energy. These resources are used extensively all levels of production, heating, transportation etc.

Renewable energy resources are increasingly being used for energy generation. These resources are environmental friendly resources. However, renewable energy conversion is weak relatively non-renewable energy conversion by means of drawbacks on investment, operating and maintenance costs, natural restriction in installation area and technological difficulties.

Investment decision for a renewable energy conversion facility arises as a difficult decision problem. It is a complicated, multi-criteria decision problem in nature. This study describes an approach as decision support tool based on AHP and GRA.

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II. LITERATURE REWIEW

There have been numerous studies in the literature on renewable energy technologies. Particularly, the selection problem has been interested by many researchers. This study proposes a novel solution approach for the selection problem based on AHP and GRA.

Chang and Lin [1] used grey relation analysis to analyze CO_2 emissions from 34 industries in Taiwan. They determined the factors: production, total energy consumption, coal, oil, gas and electricity uses. They stressed that industrial production has the closest relationship with whole CO_2 emission changes. Electricity consumption is the second important factor. They pointed out the economy in Taiwan relied heavily on CO_2 intensive industries, and that electricity consumption had become more important for economic growth alike other industrialized countries. They said policy makers on energy faced with a confliction between growth rate and electricity usage which influence directly CO_2 emission mitigation strategy. Wen [2] explained in this paper that the use of the grey relational grade, GM (1, N) and GM (0, N) models for the solution of breakdown probability. It was used also for reducing the harmful effects on system. It was a three stage study: determination of grey relational grade, gas breakdown analysis and using algorithm on an example problem. It was concluded with a discussion. Song and Jamalipour [3] developed a network selection procedure for 3G/wireless LAN networks. They proposed a method which is a combination of GRA and AHP. They employed their method using simulation. They had good solution for the selection of network. Yang and Chen [4] used an aggregated AHP and grey relational analysis for supplier selection problem. They calculated relative importance weightings of qualitative criteria using AHP. Then, weightings were used as coefficients of grey relational analysis model in their study. The qualitative and quantitative data were handled together and obtained the grey relational grade values. The best supplier had the highest value among others. Peng et al. [5] has examined energy consumption and environmental quality level quantitatively by using grey relational analysis for the past 8 years. They suggested to the government some precautions such as adjusting the energy consumption structure, guiding economic structure to the direction of the development of low power and speeding up technical innovation, rising energy utilization efficiency based on their findings. Lin et al. [6] conducted a grey relational analysis on the emission of CO_2 in Taiwan. They handled 37 industrial sectors in Taiwan and examined interrelation among growth rate, entire consumption of energy, and CO_2 emission. They found that a rapid pace in electricity generation during the last decade is the main reason for CO_2 emission increase in Taiwan. They mentioned that productivity in energy usage should be a governmental policy to remain competitive. Mu and Zhang [7] published a paper hierarchy grey relational analysis for optimal selection. It was based on AHP, hierarchy house of quality (HHOQ) and GRA. They provided a novel approach using GRA, house of quality and AHP together for higher accuracy. Zeng et al. [8] employed an approach for the waste water treatment alternative selection problem. This was based on AHP and GRA. They used characteristics such as multiple economic, technical and administrative performance criteria, including capital cost, operation and maintenance (O&M) cost, land area, removal of nitrogenous and phosphorous pollutants, sludge disposal effect, stability of plant operation, maturity of technology and professional skills required for O&M that represented the alternatives and evaluated four water treatment methods. Feng and Liu [9] used also grey relational analysis to analyze the energy consumption productivity by means of CO_2 emission changes. They found the most important factor on CO_2 emission is total energy consumption instead of growth rate. As a result, it was recommended a separation on energy consumption to provide efficient use of energy. Lu et al. [10] compared the Taiwan and OECD countries by means of energy utilization characteristics in transportation. When they were carrying out the methodology they used GRA. They observed the relative influence of the fuel price, the gross domestic product, the number of motor vehicles and the vehicle kilometers of travel per energy increase. Sasikumar et al. [11] presented a study in automobile industry for the problem of supplier selection. Their methodology was established on AHP and GRA. They practiced the method for validation in a well-known auto plant. Yang et al. [12] evaluated environmental concerns such as biodiversity, heterogeneous landscapes on the selection of urbanization area in Changsha City. They used AHP and GRA besides Geographic Information Systems (GIS). Their main purpose was to handle some uncertainty on landscape selection for urbanization. They had reasonable outcomes to serve policy makers. Hu [13] applied the AHP and GRA on supplier selection problem. The result showed that companies should pay attention to factors cost, financial status, delivery, product quality and customer service respectively. Aixiang [14] conducted a study in agriculture at Jiangsu province in China. GRA was used in the study and focused on agricultural energy consumption and its impacts. Peng and Wang [15] applied GRA on a design and improvement for shearing process in a flying shear machine. Consequently eccentric tilting shear mechanism was chosen as optimum mechanism. Chen and Chen [16] performed a study in semiconductor manufacturing industry. They used AHP, GRA and TOPSIS together and applied the methodology on the selection of maintenance strategy. This methodology presented is useful based on the obtained results from a real life example. Xu et al. [17] proposed a novel approach which is based on integrated AHP and GRA. They examined the current situation of coal-fired power plants by means of their thermal, environmental, and economic performance. They found that proposed method can handle performance evaluation of complex energy utilization systems for policy makers.

III. A COMBINATION OF AHP AND GRA METHODOLOGY

A. The Methodology of AHP

The decomposition of research objects into individual factors which has different levels with respect to the nature of research objects is the main conception and the first step of AHP. In the second step, a hierarchical decision system according to specific procedures is made up by their dominance relationship. The weights through distinct indices are fixed by doing pairwise comparisons at the same level. Then different objects are placed in order. The magnitude of the weights and characteristics of various objects are compared and it is resulted with a good judgment. Three steps in AHP, decomposition, judgment and synthesizing are the same way as people think. So it could be said that the AHP is a subjective weighting method. The relative importance between two comparative factors is reflected by the element values of judgment matrix. Table I shows general form of the measurement scale. It has relative importance in scale of 1-9 [17], [18].

TABLE I
EXPLANATION OF ENTRIES IN A PAIRWISE COMPARISON MATRIX

Importance degree	Descriptions	Explanation
1	Equally important	Criteria *i* and *j* are of equal importance
3	Weakly important	Criteria *i* is weakly more important than objective *j*
5	Strongly important	Criteria *i* is strongly more important than objective *j*
7	Very strongly important	Criteria *i* is very strongly more important than objective *j*
9	Extremely important	Criteria *i* is extremely more important than objective *j*
2, 4, 6, 8	Intermediate values	For example, a value of 8 means that Criteria *i* is midway between strongly and more important than objective *j*

The analytic process of AHP should pass through the subsequent steps in order [17]:

1) The pairwise comparison matrix (P) is formed

$$P = (p_{ij})_{nxn} = \begin{pmatrix} p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ p_{n1} & p_{n2} & \cdots & p_{nn} \end{pmatrix} \quad (1)$$

where p_{ij} is the importance degree of the i^{th} factor compared to the j^{th} factor.

2) The following formula is used and the elements of matrix P are normalized:

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$$\overset{Norm}{p}_{ij} = \frac{p_{ij}}{\sum_{k=1}^{n} p_{kj}}, \qquad i, j = 1,2,...,n \tag{2}$$

Then, normalization matrix, $\overset{Norm}{P}$ can be acquired

$$\overset{Norm}{P} = (\overset{Norm}{p}_{ij})_{nxn} \tag{3}$$

3) Aggregating the elements of the same line/row of normalization matrix $\overset{Norm}{P}$, we can get

$$\overset{Norm}{w}_i = \sum_{j=1}^{n} \overset{Norm}{p}_{ij}, \qquad i = 1,2,...,n \tag{4}$$

4) The weights vector W = (w_1, w_2, … , w_n) is then found through the following formula:

$$w_i = \frac{\overset{Norm}{w}_i}{\sum_{k=1}^{n} \overset{Norm}{w}_k}, \qquad i = 1,2,...,n \tag{5}$$

5) The maximum value $\lambda_{\max}$ is computed as follows:

$$\lambda_{\max} = \frac{1}{n} \sum_{i=1}^{n} \frac{(PW)_i}{w_i} \tag{6}$$

Where n is the dimension of the comparison matrix.

6) Finally, a consistency check is applied by computing the consistency ratio (CR)

$$CR = \frac{CI}{RI} \tag{7}$$

where RI is the random index. The values of RI, which change with variations in the dimensions, are shown in Table II. CI is the consistency index, and can be computed by

$$CI = \frac{\lambda_{\max} - n}{n - 1} \tag{8}$$

When CR $\leq$ 0.10, it means that the consistence of the pairwise comparison matrix is acceptable

TABLE II
RI VALUES

Dimension	1	2	3	4	5	6	7	8	9
RI	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45

B. Grey Relational Analysis

Grey system theory has been established by Deng (1982). Grey system is defined as a system having partial information. Its nature has ambiguity so it is used to solve the problems consisted of discrete data and partial information. Grey system theory's distinguish feature is that it can handle smaller data easily and can be achieved in good results. It performs this by putting the data in its regular place with proper treatment [11], [19], [20].

Modification was done by using GRA as follows, [12], [21]:

1) Let the reference sequence be

$$x_0 = (x_{01}, x_{02}, \dots, x_{0n}) \tag{9}$$

2) Represented the m sequences to be compared as

$$x_i = (x_{i1}, x_{i2}, \dots, x_{in}), \quad i = 1, 2, \dots, m \tag{10}$$

3) Normalize the sequences to guarantee that all of them are in the same order, and the normalized sequences can be denoted as

$$x_i^* = (x_{i1}^*, x_{i2}^*, ..., x_{in}^*) \quad i = 1, 2, \dots, m \tag{11}$$

For benefit x_i indices, the normalized data can be obtained by

$$x_i^* = \frac{x_{ij}}{x_{i\max}} \qquad i = 1,2,...,m, \quad j = 1,2,...,n \tag{12}$$

While for cost x_i indices, the normalized data can be obtained by

$$x_i^* = \frac{x_{i\min}}{x_{ij}} \qquad i = 1,2,...,m, \quad j = 1,2,...,n \tag{13}$$

In Eqs. (12) and (13), x_{imax} and x_{imin} refer to the maximum and minimum values of the *i*th row of the decision matrix, respectively.

4) The grey relational coefficient between the compared sequence, x_i, and the reference sequence, x_0, for the *j*th factor (j=1, 2, . . , n), was defined as:

$$\xi_{ij} = \frac{\min_i(\min_i |x_{0j} - x_{ij}^*|) + \rho \max_i(\max_j |x_{0j} - x_{ij}^*|)}{|x_{0j} - x_{ij}^*| + \rho \max_i(\max_j |x_{0j} - x_{ij}^*|)} \tag{14}$$

where x_{ij}^* is the grey relational coefficient between the *i*th index of the *j*th project to be evaluated and the *i*th element of the reference (or optimal) sequence;

where $\xi_{ij} \in [0, 1]$, x_{ij}^* is the value of factor *j* of grid *i*, ρ is the distinguishing coefficient, $\rho \in [0, 1]$, and typically $\rho = 0{,}5$.

5) The aggregated evaluation model could thus be written as follows:

$$S_i = \sum_{j=1}^{n} w_j \xi_{ij} \tag{15}$$

where S_i is the integrated evaluation value of grid i, w_j is the weight for factor *j* of grid *i*, and $S_i \in [0, 1]$.

IV. IMPLEMENTATION OF THE HIERARCHY GREY RELATIONAL ANALYSIS

The steps employed in the proposed model are depicted in Figure 1. It starts from the both qualitative and quantitative criteria definition, application of AHP to obtain the relative weights between the criteria and sub criteria and using these weights as inputs for GRA to find out the best renewable electricity generation technology.

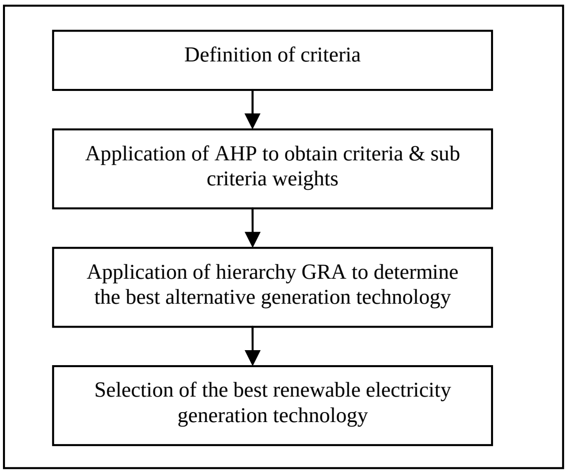

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Fig. 1. Steps in the hierarchy GRA model for renewable electricity generation technologies

A. Definitions of Criteria

We defined three main criteria into technical, economical and social. These criteria are considered based on previous studies [22]-[25]. We divided technical criteria into four sub-criteria; Efficiency (SC1), Construction period (SC2), Capacity factor (SC3) and Maximum availability (SC4). We divided economical criteria into four sub-criteria; Technical lifetime (SC5), Investment cost (SC6), Fixed & variable O&M cost (SC7) and Progress ratio (SC8). We divided social criteria into two sub-criteria; Social acceptability (SC9) and Job creation (SC10). These criteria are briefly defined in the following section:

Efficiency (SC1): The efficiency indicator used to measure energy systems' productivity which is calculated by the ratio of output energy to input energy. Efficiency is a usefulness measure which means how much useful energy can be extracted from an energy resource.

Construction period (SC2): It is a time measure to indicate how much time needed to build an energy generation facility.

Capacity factor (SC3): This is the ratio of actual production to theoretical production capacity for a plant in a certain period. In other words it is the number of full-load hours.

Maximum availability (SC4): This factor is related to availability of a power plant. Plant cannot be available because of maintenance or lack of fuel. So it is described as the amount of time that it is able to produce electricity_over a certain period, divided by the amount of the time in the period.

Technical lifetime (SC5): The technical life time of the equipment, expressed in years. The annuities are calculated for a refund period equal to the technical life time.

Investment cost (SC6): The purchase of mechanical equipment, technological installations, construction of roads and connections to the national grid, engineering services, drilling and other incidental construction work constitute investment cost. This cost item is the most used economic criterion to appraise energy systems.

Fixed & variable O&M cost (SC7): The wages of employees, and the funds spent for the energy, the products and services for the energy system operation are the one part of this cost item. The rest of it is the maintenance cost that aims to extend energy system life.

Progress ratio (SC8): Global benefit of a renewable energy technology. The Progress Ratio is a number to indicate investment progress all over the world.

Social acceptability (SC9): Peoples' thought on the energy generation systems. It cannot be computed easily due to its qualitative nature.

Job creation (SC10): Job opportunities creating by investment of energy technologies. It should be considered as factor.

B. Constitution of Hierarchy

In this section, the hierarchy GRA was carried out to the selection of the renewable electricity generation technologies. A hierarchy decision model for the problem is given in Fig. 2. The overall objective of the decision lies at the top of the hierarchy (Level 1), and criteria, sub criteria and alternatives are on the descending levels of this hierarchy (Level 2, Level 3, and Level 4, respectively). In this study, we focused on the determination of best suitable renewable electricity generation technologies among six different alternatives taken into account the criteria and sub-criteria. The criteria are economical, technical and social criteria. Sub-criteria are efficiency, construction period, capacity factor, maximum availability, technical lifetime, investment cost, fixed & variable-operation and maintenance (O&M) cost, progress ratio, job creation, social acceptability [8].

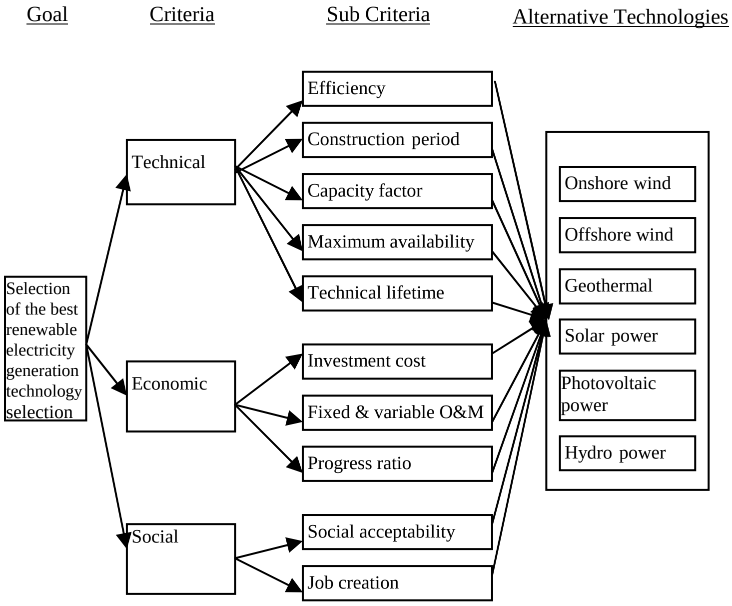

Fig. 2. A hierarchy decision model for renewable energy technology selection

C. Computation of Weights

We need to compute the weights of criteria and sub-criteria after obtaining hierarchy. These were computed based on decision makers' relative importance of their judgments on alternatives. Table III shows computed weights and consistency ratios.

TABLE III
WEIGHTS FOR CRITERIA AND SUB CRITERIA CONSIDERED BY EXPERT

Criteria	Weight	CR	Sub Criteria	Weight	CR
Technical	0.359		Efficiency(SC1)	0.236	
			Construction period (SC2)	0.047	
			Capacity factor (SC3)	0.448	0.0509
			Maximum availability (SC4)	0.185	
			Technical lifetime (SC5)	0.085	
Economic	0.581	0.0043	Investment cost (SC6)	0.115	
			Fixed & variable O&M cost (SC7)	0.182	0.0758
			Progress ratio (SC8)	0.703	
			Social acceptability (SC9)	0.750	-
Social	0.110		Job creation (SC10)	0.250	

D. Grey Relational Analysis

We found the weighting belonged to related indices of criteria and sub-criteria. Each alternative was evaluated with GRA depended on these weights for the selection of the best alternative. However criteria cannot be handled all the time as quantitative values by decision makers. In this case, the verbal statements (linguistic values) of decision makers

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were quantified by using Table IV [8]. Table V shows the linguistic values in quantity based on Table IV [22], [25].

TABLE IV
LINGUISTIC VALUES SCALE

Linguistic Values	Quantity
Excellent (E)	0.9
Good (G)	0.7
Moderate (M)	0.5
Poor (P)	0.3
Very Poor (VP)	0.1

TABLE V
AN OBJECTIVE HIERARCHY FOR SELECTING THE RENEWABLE ELECTRICITY GENERATION TECHNOLOGY

Goal	Criteria	Sub Criteria	Alternative Technologies					
			A1	A2	A3	A4	A5	A6
	Technical	SC1 (%)	P(0.3)	P(0.3)	P(0.3)	VP(0.1)	G(0.7)	VP(0.1)
		SC2 (month)	8	24	27	27	18	6
		SC3 (%)	25	40	90	32.5	45	12.5
Renewable energy technology selection		SC4 (%)	98	97	97	98	99	99
		SC5 (year)	25	25	80	25	80	25
		SC6 (€/kW)	1350	3200	7000	4500	3360	4050
	Economic	SC7 (% of inv.)	2	3.6	2	3	2	0.6
		SC8	0.9	0.95	0.95	0.925	0.95	0.82
	Social	SC9	VP (0.1)	G (0.7)	G (0.7)	E (0.9)	M (0.5)	M (0.5)
		SC10	M (0.5)	M (0.5)	G (0.7)	P (0.3)	G (0.7)	P (0.3)

Hierarchy GRA was applied based on Table V. SC2, SC6 and SC7 sub-criteria state loss so it is used Eq.3 and rest of the sub-criteria state benefit so it is used Eq.2. Table VI shows the normalized values of all sub-criteria.
All values of sub-criteria for each alternative moved on the same scale by using the linear normalization method for the purpose of comparison. Moreover, needed data were prepared for the computation of primary grey relation coefficients of sub-criteria. These were calculated by using Eq.4 and shown in Table VII. The value of ρ was 0,5 in Eq.4.

TABLE VI
NORMALIZED DATA FOR SUB CRITERIA LEVEL

Criteria	Sub Criteria	Alternative Technologies						
		X_0	A1	A2	A3	A4	A5	A6
C1	SC1	1.00	0.43	0.43	0.43	0.14	1.00	0.14
	SC2	1.00	0.75	0.25	0.22	0.22	0.33	1.00
	SC3	1.00	0.28	0.44	1.00	0.36	0.50	0.14
	SC4	1.00	0.99	0.98	0.98	0.99	1.00	1.00
	SC5	1.00	0.31	0.31	1.00	0.31	1.00	0.31
C2	SC6	1.00	1.00	0.42	0.19	0.30	0.40	0.33
	SC7	1.00	0.90	0.21	0.17	0.18	0.36	1.00
	SC8	1.00	0.95	1.00	1.00	0.97	1.00	0.86
C3	SC9	1.00	0.11	0.78	0.78	1.00	0.56	0.56
	SC10	1.00	0.71	0.71	1.00	0.43	1.00	0.43

TABLE VII
PRIMARY GREY RELATIONAL COEFFICIENTS FOR SUB CRITERIA LEVEL

Criteria	Sub Criteria	A1	A2	A3	A4	A5	A6
C1	SC1	0.088	0.088	0.088	0.060	1.000	0.060
	SC2	0.180	0.068	0.066	0.066	0.076	1.000
	SC3	0.071	0.090	1.000	0.079	0.099	0.060
	SC4	0.845	0.731	0.731	0.845	1.000	1.000
	SC5	0.074	0.074	1.000	0.074	1.000	0.074
C2	SC6	1.000	0.087	0.064	0.073	0.084	0.076
	SC7	0.355	0.065	0.062	0.063	0.079	1.000
	SC8	0.511	1.000	1.000	0.676	1.000	0.287
C3	SC9	0.058	0.198	0.198	1.000	0.110	0.110
	SC10	0.161	0.161	1.000	0.088	1.000	0.088

Secondary grey relational coefficients were calculated for criteria and shown in Table VIII. When the computation procedure used for sub-criteria was applied on the values of Table VIII, secondary grey relational coefficients for criteria was found out. These coefficients values were shown in Table IX.

TABLE VIII
WEIGHTED PRIMARY GREY RELATIONAL COEFFICIENTS FOR CRITERIA LEVEL

	A1	A2	A3	A4	A5	A6
C1	0.223	0.206	0.692	0.215	0,554	0,279
C2	0,539	0,725	0,722	0,495	0,727	0,392
C3	0,084	0,189	0,399	0,772	0,333	0,105

TABLE IX
TABLE SECONDARY GREY RELATIONAL COEFFICIENTS FOR CRITERIA LEVEL

	A1	A2	A3	A4	A5	A6
C1	0.074	0.072	0.998	0.073	0.214	0.084
C2	0.167	0.106	0.107	0.207	0.106	0.977
C3	0.058	0.067	0.101	0.999	0.087	0.059

At the end by using Eq.15, multiplication of secondary grey relational coefficient matrix (Table IX) and the weighting vector for the criterion level gives us the aggregated grey relational grade vector (Table X). As shown in Table X, the six alternatives, that is Onshore wind, Offshore wind, Geothermal power, Solar power, Hydro power and Photovoltaic power, are ranked 5, 6, 2, 3, 4 and 1, respectively. Therefore, photovoltaic power is the optimal alternative for investing in the different renewable electricity generation technologies.

TABLE X
THE INTEGRATED GREY RELATIONAL GRADE FOR EACH RENEWABLE ENERGY TECHNOLOGY

Renewable energy technology	Integrated grey relational grade	Rank
Onshore wind (A1)	0.126	5
Offshore wind (A2)	0.091	6
Geothermal power (A3)	0.381	2
Solar power (A4)	0.253	3
Hydro power (A5)	0.137	4
Photovoltaic power (A6)	0.601	1

V. CONCLUSION

The selection of renewable electricity generation technology is a difficult multi-criteria decision making problem. When uncertainty and complexity involve in this problem it became harder to handle. The new proposed solution procedure based on AHP and GRA has been employed to assess the renewable electricity generation technology alternatives. It was presented a combination of conventional AHP and GRA named by Zeng as analytical grey relational analysis (HGRA).

The individual levels of importance of the criteria are stated through the weights. So it can eliminate the bias due to subjective judgments and random effects. This approach effectively employed on the electricity generation using renewable energy technology. Decision and policy makers can use this procedure in their decision making processes. Moreover, this approach can be carried out to the similar multi-criteria decision making problems from other fields.

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