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A Hybrid Multi-Criteria Analysis Approach for the Assessment of Renewable Energy Resources Under Uncertainty

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ABSTRACT

Evaluation of renewable energy resources is a critical and complex process which requires the assessment and aggregation of multiple criteria and also the usage of appropriate data related to them. This study presents a simulation based multi-criteria model for the general evaluation of renewable energy alternatives. This model integrates Monte Carlo simulation technique with Grey Relational Analysis (GRA) method to be able to represent the variability and the uncertainty inherent in the data. Simulation based GRA method is used for ranking the renewable energy alternatives which are solar, wind, hydroelectric, biomass and geothermal energy. The effectiveness and the applicability of the proposed model is also illustrated with an application in which 5 renewable energy alternatives are evaluated according to 12 criteria.

Keywords: Renewable Energy, Multiple Criteria Evaluation, Grey Relational Analysis, Simulation

Yenilenebilir Enerji Kaynaklarının Belirsizlik Altında Değerlendirilmesi İçin Bir Hibrit Çok Kriterli Analiz Yaklaşımı

ÖZ

Yenilenebilir enerji kaynaklarının değerlendirilmesi, birden çok kriterin dikkate alınması ve bir araya getirilmesi ile bunlarla ilgili uygun verilerin kullanılmasını gerektiren kritik ve karmaşık bir süreçtir. Bu çalışma, yenilenebilir enerji alternatiflerinin genel değerlendirmesi için bir simülasyon tabanlı çok kriterli karar modeli sunmaktadır. Bu model verilerdeki belirsizlik ve değişkenliği daha iyi temsil edebilmek için Monte Carlo simülasyon tekniğini Gri İlişkisel Analiz (GİA) yöntemiyle bütünleştirmektedir. Simülasyon tabanlı GİA yöntemi, yenilenebilir enerji alternatifleri olan güneş, rüzgar, hidroelektrik, biyokütle ve jeotermal enerjinin sıralamasında kullanılmaktadır. Önerilen modelin etkinliği ve uygulanabilirliği, 5 yenilenebilir enerji alternatifinin 12 kritere göre değerlendirildiği bir uygulama ile de gösterilmektedir.

Anahtar Kelimeler: Yenilenebilir Enerji, Çok Kriterli Değerlendirme, Gri İlişkisel Analiz, Simülasyon

1. Introduction

Energy is vital for both economies and everyday life and the world's average rate of increasing energy demand is expected to increase 1.8 % per year until 2030 (EU Commission, 2003). Renewable energy resources (RES) are considered to be one of the most appropriate alternatives to conventional energy resources. Renewable energy which has different forms such as solar, hydro power, geothermal, wind power and biomass is more environmentally friendly and does not cause pollution (Li-bo & Tao, 2014). It is produced from natural, recurring and continuous outflow of energy, and does not consume any natural resource and can be naturally replenished which make it also sustainable (Tasri & Susilawati, 2014; Aydin et al., 2013; Banos et al., 2011).

Related authorities should carefully plan and form energy portfolios of the countries. Energy planning is a complex and critical task since every energy source has its own advantages and disadvantages and none can be accepted superior to another in every aspect (Çelikbilek & Tüysüz, 2016). Assessment of RES is a typical multi-criteria decision making (MCDM) problem since it contains many conflicting criteria to be considered (San Cristóbal, 2011).

MCDM methods deal with the ranking and selection of one or more among the alternatives with respect to determined criteria set. The appropriateness or suitability of an alternative mostly depends on the factors that are selected and evaluated together with their performance on the objectives. Applying MCDM methods in energy problems enables the clear recognition of the influence of subjective issues on the final ranking of alternatives (Georgopoulou et al., 1997), to handle such complex issues with low requirements, and can also work with such poor data systems (Arce et al., 2015).

MCDM methods have been widely used in the area of energy such as AHP (Hämäläinen & Karjalainen, 1992; Lee et al., 2009; Wang et al., 2010; Uyan, 2013; Ahmad & Tahar, 2014; Štreimikienė et al., 2016, ANP (Ulutaş, 2005; Aragonés-Beltrán et al., 2014; Dağdeviren & Eraslan, 2008; Atmaca & Basar, 2012), ELECTRE (Georgopoulou et al., 1997; Beccali et al., 2003; Papadopoulos & Karagiannidis, 2008), TOPSIS (Doukas et al., 2010; Şengül et al., 2015), PROMETHEE (Goumas & Lygerou, 2010; Haralambopoulos & Polatidis, 2003; Topcu & Ulengin, 2004), and AHP and VIKOR (Kaya & Kahraman, 2010; San Cristóbal, 2011). The detailed literature review about the applciations of different methods and techniques in the area of energy can also be found in (Bhowmik, 2017).

Based on the literature review, it can be concluded that assessment decisions of energy alternatives should take into consideration more than one criterion, and also appropriate data related to these criteria should be used. Due to these reasons, this study presents a hybrid MCDM approach for the general assessment of RES which are solar, wind, hydroelectric, geothermal and biomass. The proposed model integrates Monte Carlo simulation with grey relational analysis method (GRA) to better represent the variability and the uncertainty.

The organization of the paper is as follows. In section 2, GRA method and its literature is presented. In section 3, the algorithm of the proposed approach is presented. In section 4, an application of the proposed approach for the general assessment of RES alternatives is given. Finally, conclusions are presented.

2. Grey Relational Analysis

Deng (1982) proposed grey system theory for the analysis of systems which contains imprecise information. Grey relational analysis (GRA) which is consisted in grey system theory is one of the methods that can be used to solve MCDM problems. The main advantage of GRA is that it differs from classical statistical methods by its ability to assess quantitative and qualitative relationships between the factors by using relatively small amount of data (Deng, 1982). GRA has been used in many MCDM problems such as supplier selection (Yang & Chen, 2006; Golmohammadi & Mellat-Parast, 2012; Hashemi et al., 2015; Chen & Zou, 2016), machine tool selection (Samvedi et al., 2012), material selection (Chan & Tong, 2007), software selection (Huang et al., 2008), personnel selection (Zhang & Liu, 2011), and energy performance evaluation (Lee & Lin, 2011). Detailed literature about the applications of GRA and other grey based MCDM methods can be found in (Arce et al., 2015).

The algorithmic steps of the GRA are as follows:

Step 1. Establish the comparability sequences. For each alternative, comparability sequence Xi ={xi(1), xi(2),..., xi(n)} is established. This sequence includes performance values of alternative i regarding each criterion. Decision matrix is generated using comparability sequences as follows:

$$X = \begin{bmatrix} x_1(1) & x_1(2) & \cdots & x_1(n) \\ x_2(1) & x_2(2) & \cdots & x_2(n) \\ \vdots & \vdots & \cdots & \vdots \\ x_m(1) & x_m(2) & \cdots & x_m(n) \end{bmatrix} \tag{1}$$

where m is the number of alternatives (i=1,2,...,m), n is the number of criteria (j=1,2,...,n) and xi(j) is the value of the jth criterion of the ith alternative.

Step 2. Establish the reference sequence. According to comparability sequences, a reference sequence X0 ={x0(1), x0(2),..., x0(n)} is generated. This sequence consists of the best or target values of criteria.

Step 3. Normalize the data series. Normalized values of the comparability sequences are calculated by using Eqs. (2)-(4).

If the expectancy is larger-the-better,

$$x_i(j) = \frac{x_i(j) - \min_i x_i(j)}{\max_i x_i(j) - \min_i x_i(j)} \tag{2}$$

If the expectancy is smaller-the-better,

$$x_i(j) = \frac{\max_i x_i(j) - x_i(j)}{\max_i x_i(j) - \min_i x_i(j)} \tag{3}$$

If the expectancy is nominal-the-better,

$$x_i(j) = 1 - \frac{\left|x_i(j) - u_j\right|}{\max\left\{\max x_i(j) - u_j, u_j - \min x_i(j)\right\}} \tag{4}$$

where uj is the nominal performance value for criterion j.

Step 4. Calculate the grey relational coefficient. Grey relational coefficient shows the relationship between the reference sequence and comparability sequence. This coefficient is calculated using the normalized values as follows:

$$\gamma_i(j) = \frac{\Delta\min + \xi\Delta\max}{\Delta_i(j) + +\xi\Delta\max} \tag{5}$$

Where

$$\Delta_i(j) = \left|x_i(j) - x_0(j)\right| \tag{6}$$

$$\Delta_{\max} = \max_i \max_j \left|x_i(j) - x_0(j)\right| \tag{7}$$

$$\Delta_{\min} = \min_i \min_j \left|x_i(j) - x_0(j)\right| \tag{8}$$

ξ is the distinguishing coefficient and ξ ϵ [0,1]. ξ which is used to decrease the effect of Δmax is taken as 0.5 in most problems.

Step 5. Calculate the grey relational grade. Grey relational grade between the reference sequence and every comparability sequence is calculated using grey relational coefficients and criteria weights.

$$r_i = \sum_{j=1}^{n} \gamma_i(j) * w_j \tag{9}$$

where w_j is the weight of the jth criterion. The alternative with the highest grey relational grade (r_i) is evaluated as the best one.

3. Proposed Approach

In this study, a simulation integrated GRA method is proposed for the general assessment of RES alternatives. Monte Carlo simulation technique is used to represent the variability and the uncertainty inherent in the data used for GRA calculations. The algorithmic steps of the proposed hybrid MCDM approach is as follows;

Step 1. Define the criteria to be used for the assessment of RES alternatives. Criteria are established based on literature and sectoral applications.

Step 2. Gather data for each RES alternative related to the predetermined criteria. Relevant data are obtained from relevant resources.

Step 3. Establish the comparability sequences. For each alternative, comparability sequence whose elements are defined as uniform random variable with parameters (a, b) is established. The probability density function for uniform distribution is defined as in Eq. (10).

$$f(x) = \begin{cases} \dfrac{1}{(b-a)}, & a \le x \le b \\ 0, & otherwise \end{cases} \tag{10}$$

where a is the minimum value and b is the maximum value.

Step 4. Simulate the comparability sequence. Each element of the comparability matrix, which is defined as uniform random variable, is simulated. The average of the simulated elements are calculated and the decision matrix with the average values is formed as given in Eq. (1).

Step 5. Establish the reference sequence. According to comparability sequences, a reference sequence is generated which consists of the best of criteria.

Step 6. Normalize the data series. The values of the comparability sequences and reference sequence are normalized by using Eqs. (2)-(4).

Step 7. Calculate the grey relational coefficient. Grey relational coefficient which shows the relationship between the reference sequence and comparability sequence is calculated using the normalized values by using Eqs. (5)-(8).

Step 8. Calculate the grey relational grade and rank the alternatives. Grey relational grade between the reference sequence and every comparability sequence is calculated using grey relational coefficients as given in Eq. (9). The alternatives are ranked according to the grey relational grade in descending order to show the preferability. More the grey relational grade, more the alternative’s preferability is.

4. An Application of the Proposed Approach

The proposed simulation integrated multi-criteria evaluation model for the evaluation of RES alternatives which integrates Monte Carlo simulation and GRA methods aims at ranking the RES alternatives. Fig. 1 displays framework for the proposed hybrid MCDM evaluation model for the general assessment RES alternatives.

In step 1, the criteria to be used are obtained by considering literature and sectoral applications. According to the results of this, 12 criteria are determined which are given in Table 1.

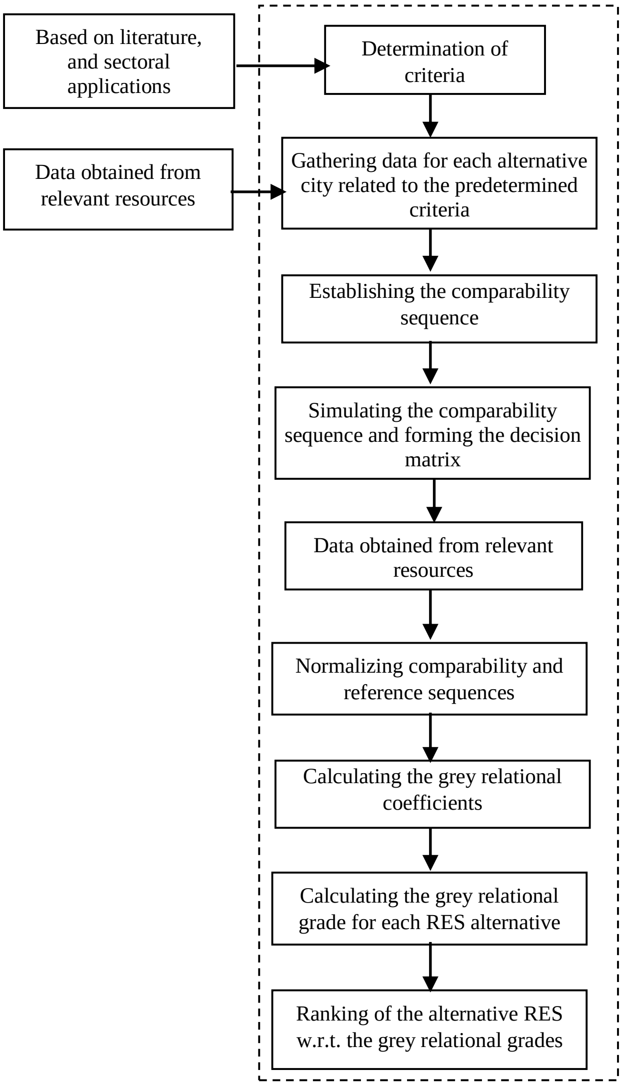

Figure 1. Proposed hybrid MCDM model framework

Criterion	**Code**	**Criterion Type**	**Reference**
Unit Cost ($/KWh)	C1	Min	US Energy Information Administration (2014)
Investment Cost ($/KWp)	C2	Min	US Energy Information Administration (2014)
Operating and Maintenance Cost ($/KWp)	C3	Min	Greenpeace (2015)
Job creation potential (person/GWh)	C4	Max	Bloomberg (2014)
Potential Power (MW)	C5	Max	Ministry of Energy and Natural Resources (2016)
Electricity Generation Capacity (GW)	C6	Max	Greenpeace (2015)
Heat Generation Capacity (GW)	C7	Max	Greenpeace (2015)
Water Consumption (Liter/MWs)	C8	Min	Fthenakis (2009)
Visual Impact	C9	Max	Applied Energy Studies (2010)
Energy Density (Energy/Area Covered)	C10	Max	Studies (2010)
Noise	C11	Max	Studies (2010)
Sustainability (GCO2/KWh emission)	C12	Min	Edenhofer (2012)

Table 1. Criteria set for RES evaluation

In step 2, the data related to the predetermined criteria are obtained from the related resources as given in Table 1. In step 3, comparability sequence is established for 5 RES alternatives. The comparability sequence includes values for solar, wind, hydroelectric, biomass and geothermal energy alternatives according to the predetermined criteria whose elements are defined as uniform random variables as given in Eq. (10). Table 2 presents the comparability sequence of RES alternatives.

Energy	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
Biomass	0,10	2,329	140	0,2	394	2	177	0	1	1	0	75
Solar	0,24	6,501	260	0,9	7328	1	151	4015	4	2	0	306
Wind	0,08	4,625	197	0,1	5286	8	0	4	3	2	2	81
Hydroelectric	0,08	2,568	103	0,3	26443	18	0	5300	5	2	3	43
Geothermal	0,05	9,138	406	2,1	7751	1	159	0	3	3	4	79

Table 2. The comparability sequence of RES alternatives

In Table 2, the criteria C9, C10 and C12 are evaluated by using linguistic variables by using the scale given in Table 3.

Lingusitic Term	Corresponding Number Representation
None	0
Very Low	1
Low	2
Medium	3
High	4
Very High	5

Table 3. The linguistic scale used in the assessment of C9, C10 and C11.

In step 4, each element of the comparability matrix whose elements are defined as uniform random variables is simulated. Random numbers are used to conduct a Monte Carlo simulation analysis to better represent the variability and the uncertainty of the comparability matrix. The performance values given in the comparability sequence that come from a uniform probability distribution with -5% and +5% around the values given in Table 2 are simulated. 1000 simulation runs are conducted to prevent the impact of random variations. The averages of the simulated elements are calculated and the decision matrix with the average values is formed as given in Table 4.

Energy	C1	C2	C3	C4	C5	C6
Biomass	0.10010	2.32902	139.92874	0.19969	394.18103	1.99932
Solar	0.24035	6.50484	259.71152	0.90048	7320.33405	0.99927
Wind	0.07998	4.62482	196.92372	0.10023	5284.52917	8.01201
Hydroelectric	0.08009	2.56616	102.89354	0.30051	26475.49730	17.98197
Geothermal	0.04994	9.13368	405.83487	2.10027	7761.62746	1.00037
Energy	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**
Biomass	176.98228	0.00000	1.00215	1.00005	0.00000	75.09751
Solar	151.08260	4011.90702	3.99637	2.00242	0.00000	305.83353
Wind	0.00000	4.00062	3.00328	2.00068	1.99940	80.97839
Hydroelectric	0.00000	5296.01222	4.99754	2.00068	3.00283	43.03679
Geothermal	159.19482	0.00000	3.00391	3.00056	3.99873	78.93478

Table 4. Simulated comparability sequences for the RES alternatives

In step 5, the reference sequence is defined using the simulated comparability sequences of alternatives (Table 4). The reference sequence in the case study is; X0 = {0.04994; 2.32902; 102.89354; 2.10027; 26475.49730; 17.98197; 176.98228; 0; 4.99754; 3.00056; 3,99873; 43,03679}.

In step 6, the normalized values for each RES alternative are calculated by using the GRA. In the application, Eq. (2) for the C4, C5, C6, C7, C9, C10 and C11 criteria, and Eq. (3) for the C1, C2, C3, C8 and C12 criteria are used. The obtained normalized values for the RES alternatives are presented in Table 5.

Energy	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Biomass	0.73660	1.00000	0.87775	0.04973	0.00000	0.05889
Solar	0.00000	0.38633	0.48235	0.40012	0.26556	0.00000
Wind	0.84224	0.66261	0.68961	0.00000	0.18750	0.41293
Hydroelectric	0.84169	0.96515	1.00000	0.10014	1.00000	1.00000
Geothermal	1.00000	0.00000	0.00000	1.00000	0.28248	0.00007
Energy	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**
Biomass	1.00000	1.00000	0.00000	0.00000	0.00000	0.87800
Solar	0.85366	0.24247	0.74942	0.50106	0.00000	0.00000
Wind	0.00000	0.99924	0.50086	0.50019	0.50001	0.85562
Hydroelectric	0.00000	0.00000	1.00000	0.50019	0.75095	1.00000
Geothermal	0.89950	1.00000	0.50102	1.00000	1.00000	0.86340

Table 5. Normalized values of the RES alternatives

In step 7, the grey relational coefficient for each data point is calculated using Eqs. (5)-(8) based on the normalized values (Table 5). The obtained grey relational coefficients for RES alternatives are presented in Table 6.

Energy	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**
Biomass	0.65497	1.00000	0.80353	0.34476	0.33333	0.34695
Solar	0.33333	0.44897	0.49133	0.45459	0.40504	0.33333
Wind	0.76016	0.59710	0.61699	0.33333	0.38095	0.45995
Hydroelectric	0.75952	0.93484	1.00000	0.35718	1.00000	1.00000
Geothermal	1.00000	0.33333	0.33333	1.00000	0.41067	0.33335
Energy	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**
Biomass	1.00000	1.00000	0.33333	0.33333	0.33333	0.80386
Solar	0.77359	0.39760	0.66615	0.50053	0.33333	0.33333
Wind	0.33333	0.99849	0.50043	0.50009	0.50000	0.77594
Hydroelectric	0.33333	0.33333	1.00000	0.50009	0.66751	1.00000
Geothermal	0.83263	1.00000	0.50051	1.00000	1.00000	0.78542

Table 6. Grey relational coefficients of RES alternatives

Finally, in step 8, the grey relational grade for each alternative is calculated using grey relational coefficients and the weights. In this application, the weights of each criterion is assumed to be equal. Then, the RES alternatives are ranked according to the obtained grey relational grades. The alternative with the highest grey relational grade is evaluated as the best alternative. The grey relational grade and rank values for RES alternatives are given in Table 7.

Energy	Grey Relational Grade	Rank
Biomass	0,60728	3
Solar	0,45593	5
Wind	0,56306	4
Hydroelectric	0,74048	1
Geothermal	0,71077	2

Table 7. Grey relational grades and ranks of the RES alternatives

According to the results given in Table 7, the best RES alternative is "hydroelectric" with a grey relational grade of 0.74048 whereas "solar" is the least preferable one with a grey relational grade of 0.45593. Hydroelectric and geothermal energies are the only ones which are above the average grey relational grade of 0.61551.

5. Conclusion

This study presents a hybrid MCDM model for the evaluation of RES which integrates Monte Carlo simulation with GRA method. Monte Carlo simulation technique is used to represent the variability and the uncertainty inherent in the data used in GRA calculations. The proposed approach enables to rank RES alternatives with respect to multiple criteria by using the relevant data, which can be helpful in many strategic decisions and actions.

Importance of this study is the usage of simulation and an MCDM method for the general assessment of RES alternatives in such an integrated manner. Another contribution is the presented Monte Carlo simulation based GRA method which can be helpful in many real life problems and applications.

The presented methodology provides the flexibility of removing or adding some new criteria which increases the applicability of the approach. In terms of practical implications, the presented methodology can be used for other MCDM problems other than renewable energy by modifying the criteria.

For further research, in addition to the application of the presented methodology for other MCDM problems and other evaluation problems related to energy, the application of the presented simulation based GRA method and its integration with other MCDM methods can be a promising area for interested researchers.

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