

Article

External Benefit Evaluation of Renewable Energy Power in China for Sustainability

Huiru Zhao ¹ and Sen Guo ^{1,2,*}

¹ School of Economics and Management, North China Electric Power University, Beijing 102206, China; E-Mail: zhaohuiru@ncepu.edu.cn

² School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI 48109-1041, USA

* Author to whom correspondence should be addressed; E-Mail: guosen@ncepu.edu.cn or guosen324@163.com; Tel.: +86-10-8079-8487; Fax: +86-10-8079-6904.

Academic Editor: Marc A. Rosen

Received: 15 February 2015 / Accepted: 10 April 2015 / Published: 23 April 2015

Abstract: China's renewable energy power has developed rapidly in recent years. Evaluating the external benefits of renewable energy power can provide a reference for the Chinese government to set diverse development goals and to implement differentiated supporting policies for different renewable energy power types, which can promote their sustainable development. In this paper, a hybrid MCDM method was applied to evaluate the external benefits of China's renewable energy power. Firstly, the impacts of renewable energy power accessing the power grid for multiple stakeholders in the electric power system were analyzed. Secondly, the external benefit evaluation index system for renewable energy power was built from the economic, social and environmental factors, based on the concept of sustainability. Then, the basic theory of the hybrid MCDM method employed in this paper was introduced in two parts: the superiority linguistic ratings and entropy weighting method for index weight determination and the fuzzy grey relation analysis for ranking alternatives. Finally, the external benefits of wind power, solar PV power and biomass power were evaluated. Taking a regional electric power system as an example, the results show that PV power has the greatest external benefit, followed by wind power and biomass power. Therefore, more policies supporting PV power should be put in place to promote the harmonious and sustainable development of the whole renewable energy power industry.

Keywords: renewable energy power; external benefit evaluation; hybrid MCDM method; China; sustainability

1. Introduction

In 1987, the United Nations World Commission on Environment and Development (WCED) published a report entitled “Our Common Future”, which proposed a term, “sustainable development” [1]. Building a resource-saving and environment-friendly society is a strategic mission for China’s economic and social development [2]. Under the dual constraints of global fossil energy’s increasing depletion and the ecological environment’s rapid deterioration, developing renewable energy has become a strategic choice for building a sustainable energy system and achieving a low-carbon economy in many countries, which is also an important path for implementing the concept of sustainable development [3,4]. Especially for China, as the largest energy consumer and producer in the world, exploring and developing renewable energy has become imperative and urgent under current constraints on resource endowment, consumption habits and technological dependence. In China, fossil energy (including coal, petroleum and natural gas) consumption has a long-term dominant role in the national primary energy consumption structure. At the end of 2013, the consumption shares of coal, petroleum and natural gas were 67.5%, 17.8% and 5.1% respectively, while new and renewable energy consumption had a 9.6% share of the total energy consumption [5]. China needs make greater efforts to develop new and renewable energy sources to tackle the issues that face it, such as energy security and environmental protection.

China’s “Renewable Energy Law” implemented in 2006 proposes vigorously exploiting and developing renewable energy resources. In 2007, the “Medium and Long Term Development Plan for Renewable Energy” issued by the China Development and Reform Commission set a development goal of renewable energy consumption making up 15% of total energy consumption in 2020 [6,7]. In the last few years, the haze occurring in many provinces and cities has also highlighted the need to develop renewable energy to replace traditional fossil fuels. In this context, renewable energy has been more and more emphasized by the government and the public. In the past ten years, the Chinese government has provided many subsidies for renewable energy power development [8]. At the end of 2013, the on-grid installed capacity of wind power, solar PV power and biomass power increased to 77.16 million kW, 14.79 million kW and 12.23 million kW, respectively. However, there are some issues that need to be solved in the renewable energy power industry, such as the low technology level and unbalanced industrial development [9]. Renewable energy power is an important way of utilizing renewable energy resources [10]. Developing renewable energy power needs clear development goals and effective policy support. An external benefit evaluation on renewable energy power accessing the power grid can identify the comprehensive impacts of different renewable energy power types on multiple stakeholders, which can act as a reference for Chinese government when setting diverse development goals and implementing differentiated supporting policies for different renewable energy types. It can also promote the sustainable development of the renewable energy power industry in China.

Currently, some studies related to the non-technical impacts (such as the economic impact and environmental impact) of renewable energy power accessing the power grid have been conducted. Delarue *et al.* [11] employed the mixed integer linear programming (MILP) and advanced unit commitment (UC) models to study the actual effects of wind power on overall electricity generation costs and CO₂ emissions in Belgium. Holttinen and Tuhkanen [12] applied the EMPS power market model and the EFOM energy system model to assess the effects of large-scale wind production on CO₂ abatement in the Nordic countries. Ummels *et al.* [13] used a unit commitment and economic dispatch (UC-ED) method to assess the impacts of large-scale wind power on system operations from cost, reliability, and environmental perspectives. Hirth [14] adopted the regression analysis of market data and the EMMA calibrated model of the European electricity market to study the market value of solar and wind power with penetration and how policies and prices affect the market value. Keith *et al.* [15] analyzed the possible climatic impacts (including global-mean surface temperature, emissions of CO₂ and air pollutants) of wind power at regional to global scales by using two general circulation models and several parameterizations of the interaction of wind turbines with the boundary layer. Morales *et al.* [16] proposed a stochastic programming market-clearing model spanning a daily time horizon to analyze the economic valuation of reserves in power systems with high penetration of wind power. Delucchi and Jacobson [17] studied the economics of wind, water, and solar power (WWS) generation and transmission, the economics of WWS use in transportation, and policy measures needed to enhance the viability of a WWS system. Katzenstein and Apt [18] evaluated the effects of wind and solar power on NO_x and CO₂ emissions by modeling a wind or solar photovoltaic plus gas system using measured 1-min time-resolved emissions and heat rate and power data. Turney and Fthenakis [19] evaluated the land use and life cycle CO₂ emission of large-scale solar power plants compared with that of coal-based electricity. Heller *et al.* [20] proposed a willow biomass production model to study the life cycle energy and environmental benefit effects of generating electricity from willow biomass. Santisirisomboon *et al.* [21] estimated the impact of biomass power generation on power generation expansion planning and mitigating carbon dioxide emission from the power sector. To the best of our knowledge, external benefit evaluations of renewable energy power which simultaneously takes the economic, social and environmental aspects into account are rarely conducted. Therefore, the external benefit evaluation of renewable energy power, comprehensively considering economic benefits, social benefits and environmental benefits based on sustainability, will be studied in this paper. This study should be an important topic for the sustainable development of renewable energy power industry and can also fill a current research gap.

The external benefits of renewable energy power consist of positive effects and negative effects of renewable energy power accessing the power grid on multiple stakeholders in the electric power system. The positive effects include pollutant emission reduction, employment increase, energy security enhancement, and so on; the negative effects include declining revenues for the power grid company and power generation enterprise, increased expenses for electric power consumers, and so on. Among these effects, some can be quantitatively accounted, such as the pollutant emission reduction and revenue decline for the power grid company, but some can only be estimated using subjective experiences from experts and practitioners, such as the energy security enhancement. Therefore, the external benefit evaluation of renewable energy power is a multi-criteria decision making (MCDM) issue which needs to consider multiple conflicting criteria. Furthermore, some

criteria can only be estimated using personal subjective experience, which produces the characteristics of fuzziness and uncertainty. Therefore, more accurately, the external benefit evaluation of renewable energy power is a fuzzy MCDM issue.

There are many fuzzy MCDM methods for evaluating and ranking alternatives, such as fuzzy-TOPSIS [22,23], fuzzy-VIKOR [24,25], fuzzy-ELECTRE [26,27], fuzzy-GRA [28,29]. The fuzzy-GRA (Grey Relational Analysis) method combines fuzzy set theory and conventional GRA, which can remove the subjective limitation of decision makers and tackle the issues of incomplete information and unknown distribution type. Therefore, fuzzy-GRA has been employed in many fields, including investment company selection [30], service quality evaluation [31], system analysis engineer selection [32], and so on. It is very unfortunate to find that the fuzzy-GRA has rarely been applied to issues related to renewable energy. Therefore, the extended fuzzy-GRA method will be employed to perform the external benefit evaluation of renewable energy power in this paper. Meantime, the entropy weighting method (a kind of objective weighting method) and superiority linguistic ratings (a kind of subjective weighting method) will be combined to determine the index weights, which can embody the conscious tendencies of decision-makers and reflect the essential information from the index data.

The rest of this paper is organized as follows: Section 2 analyzes the impacts of renewable energy power accessing the power grid for multiple stakeholders in the electric power system; the external benefit evaluation index system of renewable energy power will be built in Section 3; Section 4 introduces the basic hybrid fuzzy MCDM theory used in this paper; the external benefits of three renewable energy power types, namely wind power, solar PV power and biomass power, will be evaluated in Section 5; and Section 6 provides conclusions.

2. Impacts Analysis of Renewable Energy Power Accessing the Power Grid

The impacts analysis of renewable energy power accessing the power grid in this paper focuses on the non-technical impacts, such as economic impact, social impact and environmental impact. Wind power and solar PV power have stochastic, volatile and uncertain characteristics, and biomass power often has a fuel shortage issue. The large-scale penetration of renewable energy power will have certain impacts on multiple stakeholders in China's electric power system, including power generation enterprises, power grid companies, electricity consumers and the environment, as well as society in general [33–36]. The detailed impacts are analyzed below.

2.1. Impacts on Conventional Power Generation Enterprises

Stochastic, volatile and uncertain renewable energy power generation will disturb the safe and stable operation of the electric power system and then cause power supply quality to deteriorate [37]. To deal with this issue, power grid dispatching agencies have to change the operation mode of conventional power generation units, especially the peak-shaving units. If this happens, the power generation output of conventional thermal power will adjust more frequently than before and have to participate in peak load regulation. Meanwhile, the turn-on and turn-off times of conventional thermal power will also increase. Therefore, renewable energy power accessing the power grid will increase the fuel and maintenance costs and shorten the lifespan of conventional thermal power units. Consequently,

renewable energy power accessing the power grid will have negative impacts on conventional power generation enterprises.

2.2. Impacts on Power Grid Companies

To tackle the negative effects (such as power supply quality degradation) caused by on-grid renewable energy power and ensure the safe and stable operation of the electric power system, the power grid company has to install more static reactive power compensation devices and filtering devices, and purchase more reserve ancillary services, both of which will require additional expenditures. Meanwhile, on-grid supporting facilities for renewable energy power need to be built, such as overhead transmission lines and substation equipment, which will increase the equipment investment and maintenance costs of power grid companies. Therefore, renewable energy power accessing the power grid will also have negative impacts on power grid companies.

2.3. Impacts on Electric Power Consumers

Renewable energy power accessing the power grid will cause voltage fluctuation and harmonic waves, which will lower the power supply service level for electric power consumers. For example, the large-scale penetration of wind power will have negative effects on the daily production of factories and living conditions of residents due to the decreased power supply quality. Meanwhile, large-scale wind power access to the power grid will require long-distance power transmission. To deliver the wind power generated to other load centers, wind farms need to connect to the high-voltage transmission grid. However, due to the weak low-voltage ride-through capability of wind power, an off-grid incident usually has a higher probability of occurrence. Once this happens, the power grid will suffer obvious voltage and frequency fluctuations, and then the electrical equipment will be affected, which may cause some economic losses. The development of solar PV power in China will encounter the similar issues. Therefore, renewable energy power accessing the power grid will have negative impacts on electric power consumers.

2.4. Impacts on Environment and Society

In China, renewable energy power will initially be scheduled by power grid dispatching agencies based on national support policies [38]. So, renewable energy power generation will be a substitute for a portion of conventional power generation, especially thermal power generation. The reduction of conventional thermal power generation will decrease fossil fuel (such as coal) consumption, which could reduce environmental pollutant emissions and enhance energy safety. Accessibility and affordability of energy resources are of the greatest importance for the economic development and social stabilization of a nation. Renewable energy power can be substituted for conventional power generation types, such as thermal power which uses fossil fuels (*i.e.*, coal, oil and natural gas) to generate electric power. Therefore, renewable energy power development can contribute to national energy security enhancement due to decreasing dependence on fossil fuels, and it can also reduce environmental pollutant emissions, such as greenhouse gases (GHG) and particulate matter. Meanwhile, renewable energy power generation can reduce the water consumption of conventional

thermal power units owing to its generation reduction. The construction of renewable energy power projects can also create more job opportunities, increase government fiscal revenue, and promote regional economy growth.

However, renewable energy power accessing the power grid will also have negative impacts on the environment and society. The construction and operation of wind power farms and solar PV plants may have negative effects on the living conditions of nearby residents and the natural ecosystem. For example, the noise produced by the wind power units' operation will cause inconvenience to local residents; the installation of wind power units and solar panels will occupy plenty of land, which may destroy local vegetation and disrupt the normal habitat of local animals due to the construction and operation of renewable energy power plants; the continued rotation of large wind turbine blades will generate wind-sweeping noise and machine operation noise, which will have a huge impact on the feeding and lives of birds, and fan blade rotation will sometimes kill birds. Consequently, renewable energy power accessing the power grid will have positive and negative impacts on the environment and society.

3. External Benefit Evaluation Index System for Renewable Energy Power

Evaluating the external benefits of renewable energy power is a systems engineering issue, which is related to several aspects such as economy, society and environment. Based on the above analysis in Section 2 and related literature, the hierarchical structure of the external benefit evaluation index system for renewable energy power is built from a sustainability perspective, which is shown in Figure 1. It includes four levels, namely the goal, criteria, index and alternative. The goal level is the external benefit evaluation for renewable energy power; the criteria level contains economic benefit, social benefit and environmental benefit; the index level includes 11 indicators, namely power grid company revenue reduction, power generation enterprise cost increase, electric power consumer expenditure increase, economic growth promotion degree, energy security enhancement degree, employment increase, fiscal tax increase, technical innovation promotion degree, environmental pollutant emission reduction, water savings, and bird and vegetation damage; and the alternative level consists of wind power, solar PV power and biomass power.

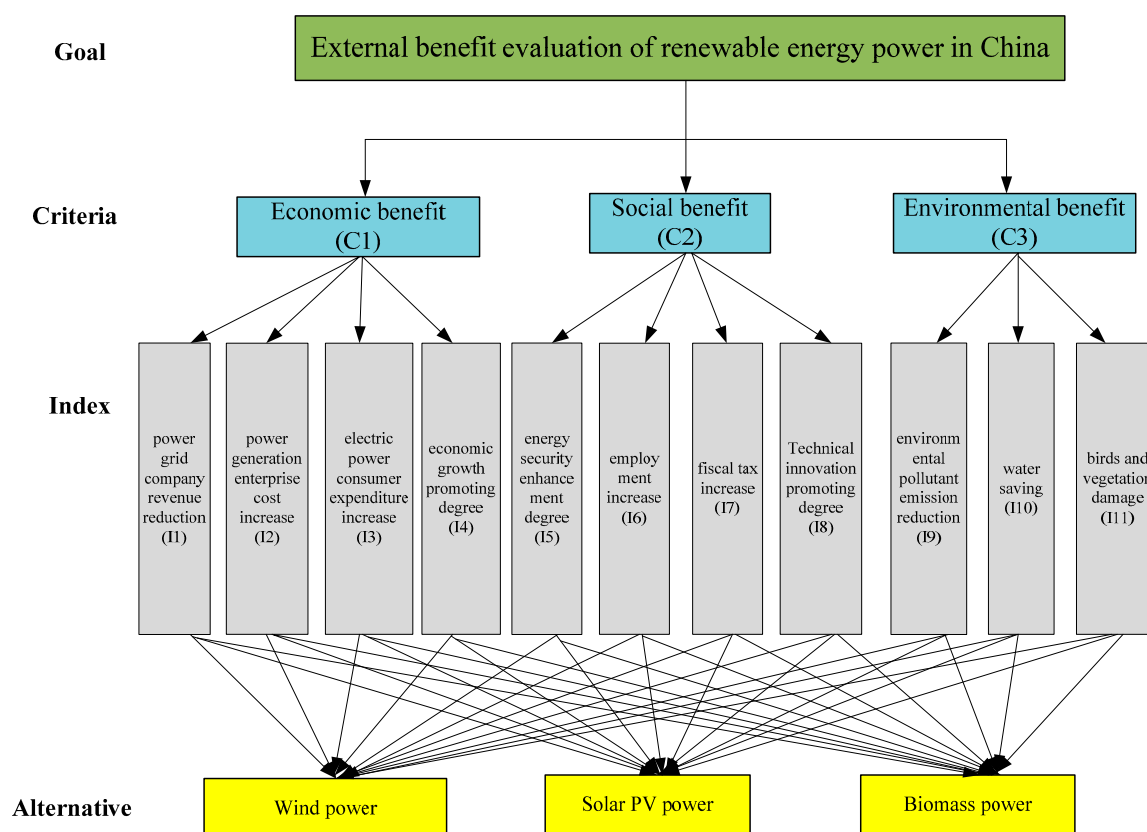


Figure 1. Hierarchical structure of external benefit evaluation index system for renewable energy power.

3.1. Economic Benefit Criteria

The economic benefit (C1) of renewable energy power accessing the power grid refers to the revenue (namely positive benefit) and cost (namely negative benefit) increases for multiple stakeholders in the electric power system caused by on-grid renewable energy power. It includes power grid company revenue reduction (I1), power generation enterprise cost increase (I2), electric power consumer expenditure increase (I3), and economic growth promotion degree (I4). Of these, I1, I2 and I3 are minimal-type (*i.e.*, the smaller the better) quantitative indices measured in monetary value; I4 is a maximum-type (*i.e.*, the larger the better) qualitative index measured in superiority linguistic ratings of decision-makers.

3.2. Social Benefit Criteria

The social benefit (C2) of renewable energy power accessing the power grid refers to the promotion (positive benefit) or inhibition (negative benefit) on social factors (such as employment and social security) due to on-grid renewable energy power. It includes energy security enhancement degree (I5), employment increase (I6), fiscal tax increase (I7) and technical innovation promotion degree (I8). Of these, I5, I6, I7 and I8 are maximum-type indices; I5 and I8 are qualitative indices, and I6 and I7 are quantitative indices.

3.3. Environmental Benefit Criteria

The environmental benefit (C3) of renewable energy power accessing the power grid refers to the protection (positive benefit) or damage (negative benefit) on natural resources (such as air and water) and ecological systems (such as animals and plants or atmospheric and soil environments) due to on-grid renewable energy power. It includes environmental pollutant emission reduction (I9), water savings (I10), and bird and vegetation damage (I11). Of these, I9 and I10 are maximum-type indices, and I11 is a minimal-type index; I9, I10 and I11 are quantitative indices.

From the above analysis, the external benefit evaluation indicators for renewable energy power and their attributes and types are listed in Table 1. For a quantitative index, we can obtain the index value based on empirical calculation; for a qualitative index, the index value can be acquired using the expert investigation method.

Table 1. External benefit evaluation index of renewable energy power.

Criteria	Index	Index attribute	Index type
Economic benefit	Power grid company revenue reduction (I1)	quantitative	minimal
	Power generation enterprise cost increase (I2)	quantitative	minimal
	Electric power consumer expenditure increase (I3)	quantitative	minimal
	Economic growth promotion degree (I4)	qualitative	maximum
Social benefit	Energy security enhancement degree (I5)	qualitative	maximum
	Employment increase (I6)	quantitative	maximum
	Fiscal tax increase (I7)	quantitative	maximum
	Technical innovation promotion degree (I8)	qualitative	maximum
Environmental benefit	Environmental pollutant emission reduction (I9)	quantitative	maximum
	Water savings (I10)	quantitative	maximum
	Bird and vegetation damage (I11)	quantitative	minimal

4. Basic Theory of the Hybrid MCDM Method

Due to the characteristics of evaluation object, a hybrid MCDM method is employed in this paper. The hybrid MCDM for evaluating the external benefit of renewable energy power consists of two parts. One part is the weight determination of objective and subjective indices using decision makers' superiority linguistic ratings (subjective weighting method) and the entropy weighting method (objective weighting method); the other part is ranking alternatives and optimal alternative selection by using the extended fuzzy grey relational analysis (fuzzy-GRA) method.

4.1. Superiority Linguistic Ratings and Entropy Weighting Method for Index Weight Determination

Fuzzy set theory, proposed by Zadeh (1965), is an extension of the classical notion of set theory, which can solve the issues in an environment of uncertainty [39]. A fuzzy set \tilde{a} is a pair (U, m) where U is a set and $m: U \rightarrow [0,1]$ is the membership function, provided by $\mu_{\tilde{a}}(x)$. Each element x in a universe of discourse X is mapped to a real number in the interval $[0, 1]$ by the membership function $\mu_{\tilde{a}}(x)$.

A triangular fuzzy number is represented as a triplet $\tilde{a} = [a^L, a^M, a^R]$, and its membership function $\mu_{\tilde{a}}(x)$ is expressed as

$$\mu_{\tilde{a}}(x) = \begin{cases} 0 & x < a^L \\ \frac{x - a^L}{a^M - a^L} & a^L \leq x < a^M \\ \frac{a^R - x}{a^R - a^M} & a^M \leq x \leq a^R \\ 0 & x > a^R \end{cases} \tag{1}$$

where a^L, a^M, a^R are crisp numbers and $-\infty < a^L \leq a^M \leq a^R < \infty$. a^L and a^R are the lower and upper bounds of available area for evaluation data respectively, reflecting the fuzziness of the evaluation index.

To quantify the index and rank the alternatives in the fuzzy environment, the graded mean integration representation method (*GMIR*) proposed by Chen and Hsieh is employed to calculate the converted value of a triangular fuzzy number for ranking in this paper [40]. By using *GMIR* method, the graded mean integration representation value $R(\tilde{a}_i)$ of triangular fuzzy number $\tilde{a}_i = [a_i^L, a_i^M, a_i^R]$ can be calculated as

$$R(\tilde{a}_i) = \frac{a_i^L + 4a_i^M + a_i^R}{6} \tag{2}$$

In order to transform the linguistic terms (represented by a word or a sentence) into triangular fuzzy numbers, the transformation rules between the linguistic variables and fuzzy ratings used for the alternatives with respect to subjective indices are listed in Table 2, and the transformation rules between the linguistic variables and fuzzy ratings used for the index weight determination are listed in Table 3 [23,28].

Table 2. Linguistic terms transformation rule for the ratings of alternatives with respect to subjective indices.

Linguistic Term	Membership Function
Very poor (VP)	(0,0,0.2)
Poor (P)	(0,0.2,0.4)
Fair (F)	(0.3,0.5,0.7)
Good (G)	(0.6,0.8,1)
Very good (VG)	(0.8,1,1)

Table 3. Linguistic terms transformation rule for the ratings of index weight.

Linguistic Term	Membership Function
Very low (VL)	(0,0,0.3)
Low (L)	(0,0.3,0.5)
Medium (M)	(0.2,0.5,0.8)
High (H)	(0.5,0.7,1)
Very high (VH)	(0.7,1,1)

The entropy weighting method is an objective method for index weight determination, which can effectively reflect the essential information of the index among different alternatives and measure the useful information implied in the index data. Many papers have introduced the basic principles and calculation steps for the entropy weighting method, such as [41] and [42], so this method will not be introduced in detail in this paper.

In this paper, the objective index weights are determined by combining the superiority linguistic ratings of decision-makers and the entropy weighting method, and the subjective index weights are assigned by the superiority linguistic ratings of decision-makers. The combination of a subjective weighting method (*i.e.*, superiority linguistic ratings of decision-makers) and an objective weighting method (*i.e.*, the entropy weighting method) not only can embody the conscious tendencies of decision-makers, but also can reflect the essential information and measure the useful information implied in the index data among different alternatives.

Suppose there are p objective indices and $n - p$ ($p \leq n$) subjective indices. Let $\tilde{s}_{kj} = (s_{kj}^L, s_{kj}^M, s_{kj}^R)$, $0 \leq s_{kj}^L \leq s_{kj}^M \leq s_{kj}^R \leq 1$, $k = 1, 2, \dots, p, \dots, n$, $j = 1, 2, \dots, r$ be the superiority linguistic ratings assigned to index I_k by decision-maker D_j , and the transformation rules between the linguistic variables and fuzzy ratings are given in Table 3. Then, the aggregated fuzzy weights $\tilde{s}_k = (l_k^L, l_k^M, l_k^R)$ for the index I_k can be calculated by

$$\tilde{s}_k = (1/r) \otimes (\tilde{s}_{k1} \oplus \dots \oplus \tilde{s}_{kj} \oplus \dots \oplus \tilde{s}_{kr}) \tag{3}$$

where $s_k^L = \sum_{j=1}^r \frac{s_{kj}^L}{r}$, $s_k^M = \sum_{j=1}^r \frac{s_{kj}^M}{r}$, $s_k^R = \sum_{j=1}^r \frac{s_{kj}^R}{r}$.

The normalized index weight u_k of all indices using the subjective weighting method can be calculated according to Equation (4).

$$u_k = \frac{R(\tilde{s}_k)}{\sum_{k=1}^n R(\tilde{s}_k)}, \quad k = 1, 2, \dots, n \tag{4}$$

Allow a_{ik} be the crisp value of alternative A_i in terms of objective index I_k ($k = 1, 2, \dots, p$). Then the objective weight λ_k of objective index I_k can be calculated by using the entropy weighting method.

Define

$$o_k = \frac{u_k}{\sum_{k=1}^p u_k}, \quad k = 1, 2, \dots, p \tag{5}$$

Then, the integrated weight z_k of the objective index I_k can be obtained by

$$z_k = \left[\frac{\lambda_k \times o_k}{\sum_{k=1}^p (\lambda_k \times o_k)} \right] \times \left(\sum_{k=1}^p u_k \right), \quad k = 1, 2, \dots, p \tag{6}$$

Therefore, the integration weights w_k of all indices (including objective indices and subjective indexes) can be obtained by

$$w_k = \begin{cases} z_k, k = 1, 2, \dots, p \\ u_k, k = p + 1, p + 2, \dots, n \end{cases} \quad (7)$$

4.2. Extended Fuzzy Grey Relation Analysis for Ranking

For the external benefit evaluation of renewable energy power, some indicators can be represented by a crisp value, such as I1 and I2. However, some indicators such as I4 and I5 cannot be represented by crisp value due to fuzziness and incomplete information, which can only be represented by a fuzzy number, namely a triangular fuzzy number in this paper. Therefore, during the evaluation, there are two representation formats for indices, *i.e.*, a crisp value and triangular fuzzy number, which can characterize the actual situation of evaluation indices and enhance the reasonability and effectiveness of the quantification process. The extended fuzzy grey relation analysis method employed in this paper combines the traditional grey relation analysis method and fuzzy set theory, which is more valid and effective for evaluating the external benefit of renewable energy power in a fuzzy environment.

The initial hybrid decision matrix A , which includes a crisp value and a triangular fuzzy number, can be shown as follows:

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1p} & \tilde{a}_{1,p+1} & \cdots & \tilde{a}_{1,n} \\ a_{21} & a_{22} & \cdots & a_{2p} & \tilde{a}_{2,p+1} & \cdots & \tilde{a}_{2,n} \\ \vdots & \vdots & \cdots & \vdots & \vdots & \vdots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mp} & \tilde{a}_{m,p+1} & \cdots & \tilde{a}_{m,n} \end{bmatrix} \quad (8)$$

where a_{ik} is the crisp value representing the k th objective evaluation index value of alternative i , $i = 1, 2, \dots, m; k = 1, 2, \dots, p$; \tilde{a}_{ik} is the triangular fuzzy number representing the k th subjective evaluation index value of alternative i , $i = 1, 2, \dots, m; k = p + 1, p + 2, \dots, n$.

$$\tilde{a}_{ik} = \frac{1}{r} \sum_{j=1}^r \tilde{a}_{ik}^j = \left[\frac{1}{r} \sum_{j=1}^r a_{ik}^{jL}, \frac{1}{r} \sum_{j=1}^r a_{ik}^{jM}, \frac{1}{r} \sum_{j=1}^r a_{ik}^{jR} \right] \quad (9)$$

where \tilde{a}_{ik}^j is the triangular fuzzy number representing the k th subjective evaluation index value of alternative i given by expert j , $i = 1, 2, \dots, m; k = p + 1, p + 2, \dots, n; j = 1, 2, \dots, r$.

The calculation steps of the extended fuzzy grey relation analysis (fuzzy-GRA) method for alternative ranking and selection are as follows.

Step 1: Index value standardization

In order to eliminate the index type and dimension effects on the evaluation, index value standardization must be done. For the external benefit evaluation of renewable energy power, there are maximum-type indices and minimum-type indices, which are represented by crisp values or triangular fuzzy numbers. Wei [43] proposed the normalization methods for crisp numbers, interval numbers, and triangular numbers. Wang *et al.* [44] proposed the normalization methods for maximum-type indices

and minimum-type indices. With reference to the above two references, the index value standardization will be performed according to Equations (10)–(13).

For maximum-type index a_{ik} with a crisp value, the standardization value b_{ik} can be calculated by

$$b_{ik} = \frac{a_{ik}}{\sum_{i=1}^m a_{ik}} \quad (i = 1, 2, \dots, m; k = 1, 2, \dots, p) \tag{10}$$

For maximum-type index a_{ik} with a triangular fuzzy number, the standardization value b_{ik} can be calculated by

$$\tilde{b}_{ik} = \left(\frac{\tilde{a}_{ik}}{\max_i \{\tilde{a}_{ik}\}} \right) = \left[\frac{a_{ik}^L}{\max_i \{a_{ik}^L, a_{ik}^M, a_{ik}^R\}}, \frac{a_{ik}^M}{\max_i \{a_{ik}^L, a_{ik}^M, a_{ik}^R\}}, \frac{a_{ik}^R}{\max_i \{a_{ik}^L, a_{ik}^M, a_{ik}^R\}} \right] \tag{11}$$

$(i = 1, 2, \dots, m; k = p + 1, p + 2 \dots, n)$

For minimum-type index a_{ik} with a crisp value, the standardization value b_{ik} can be calculated by

$$b_{ik} = \frac{1/a_{ik}}{\sum_{i=1}^m 1/a_{ik}} \quad (i = 1, 2, \dots, m; k = 1, 2, \dots, p) \tag{12}$$

For minimum-type index a_{ik} with a triangular fuzzy number, the standardization value b_{ik} can be calculated by

$$\tilde{b}_{ik} = \left(\frac{\min_i \{\tilde{a}_{ik}\}}{\tilde{a}_{ik}} \right) = \left(\frac{\min_i \{a_{ik}^L, a_{ik}^M, a_{ik}^R\}}{a_{ik}^R}, \frac{\min_i \{a_{ik}^L, a_{ik}^M, a_{ik}^R\}}{a_{ik}^M}, \frac{\min_i \{a_{ik}^L, a_{ik}^M, a_{ik}^R\}}{a_{ik}^L} \right) \tag{13}$$

$(i = 1, 2, \dots, m; k = p + 1, p + 2 \dots, n)$

Then, we can obtain the standardize evaluation index matrix B with a crisp value and triangular fuzzy number.

$$B = \begin{bmatrix} b_{11} & b_{12} & \dots & b_{1p} & \tilde{b}_{1,p+1} & \dots & \tilde{b}_{1,n} \\ b_{21} & b_{22} & \dots & b_{2p} & \tilde{b}_{2,p+1} & \dots & \tilde{b}_{2,n} \\ \vdots & \vdots & \dots & \vdots & \vdots & \vdots & \vdots \\ b_{m1} & b_{m2} & \dots & b_{mp} & \tilde{b}_{m,p+1} & \dots & \tilde{b}_{m,n} \end{bmatrix} \tag{14}$$

Step 2: Determine the referential sequence

A referential sequence in Grey system theory is a benchmarking sequence which is used for measuring the different between it and other sequences [45]. The referential sequence B_0 with a crisp value and triangular fuzzy number can be calculated using Equation (15).

$$B_0 = \left(\underbrace{b_{0k}}_{k=1,2,\dots,n} \right) = \left(\underbrace{\max_i b_{ik}}_{k=1,2,\dots,p}, \underbrace{\max_i \tilde{b}_{ik}}_{k=p+1,\dots,n} \right) \tag{15}$$

Step 3: Calculate the distance

Let $B_i (i = 1, 2, \dots, m)$ be the comparative sequences.

$$B_i = \left(\underbrace{b_{ik}}_{k=1,2,\dots,p}, \underbrace{\tilde{b}_{ik}}_{k=p+1,\dots,n} \right), i = 1, 2, \dots, m \tag{16}$$

Let $d_{0i}(k)$ be the distance between the referential sequence B_0 and a comparative sequence B_i with respect to index k . There are some methods for calculating the distance between two triangular fuzzy numbers. A modified geometrical distance with the advantages of easy implementation and powerful concept is employed to calculate the distance between two triangular fuzzy numbers in this paper [28,40]. Therefore, the distance $d_{0i}(k)$ can be calculated by Equation (17).

$$d_{0i}(k) = \left\{ \underbrace{d_{0i}(k)}_{k=1,2,\dots,p}, \underbrace{d_{0i}(k)}_{k=p+1,\dots,n} \right\} = \left\{ \underbrace{|b_{0k} - b_{ik}|}_{k=1,2,\dots,p}, \underbrace{\left[\frac{(b_{0k}^L - b_{ik}^L)^2 + 2(b_{0k}^M - b_{ik}^M)^2 + (b_{0k}^R - b_{ik}^R)^2}{4} \right]^{1/2}}_{k=p+1,\dots,n} \right\} \tag{17}$$

Step 4: Calculate the grey relational coefficient

The grey relational coefficient $\gamma(B_0^k, B_i^k)$ of alternative i from the ideal one with respect to index k can be calculated using Equation (18).

$$\gamma(B_0^k, B_i^k) = \frac{(\min_i \min_k d_{0i}(k) + \zeta \max_i \max_k d_{0i}(k))}{(d_{0i}(k) + \zeta \max_i \max_k d_{0i}(k))} \tag{18}$$

where $\min_i \min_k d_{0i}(k)$ and $\max_i \max_k d_{0i}(k)$ represent the minimum and maximum element of $d_{0i}(k)$, respectively; ζ is a distinguishing coefficient which ranges between 0 and 1. In general, when the relative conditions among sequences and alternative elements are uncertain, setting $\zeta = 0.5$ is a better choice [46].

Step 5: Calculate the Grey relational grade

The Grey relational grade $\gamma(B_0, B_i)$ of alternative i from the ideal one can be calculated by Equation (19).

$$\gamma(B_0, B_i) = \sum_{k=1}^n w_k \times \gamma(B_0^k, B_i^k) \tag{19}$$

Therefore, according to the obtained Grey relational grade, the alternatives can be ranked. The alternative with the maximum Grey relational grade should be selected as the optimal one.

The framework of the hybrid MCDM approach for external benefit evaluation of renewable energy power in China is shown in Figure 2.

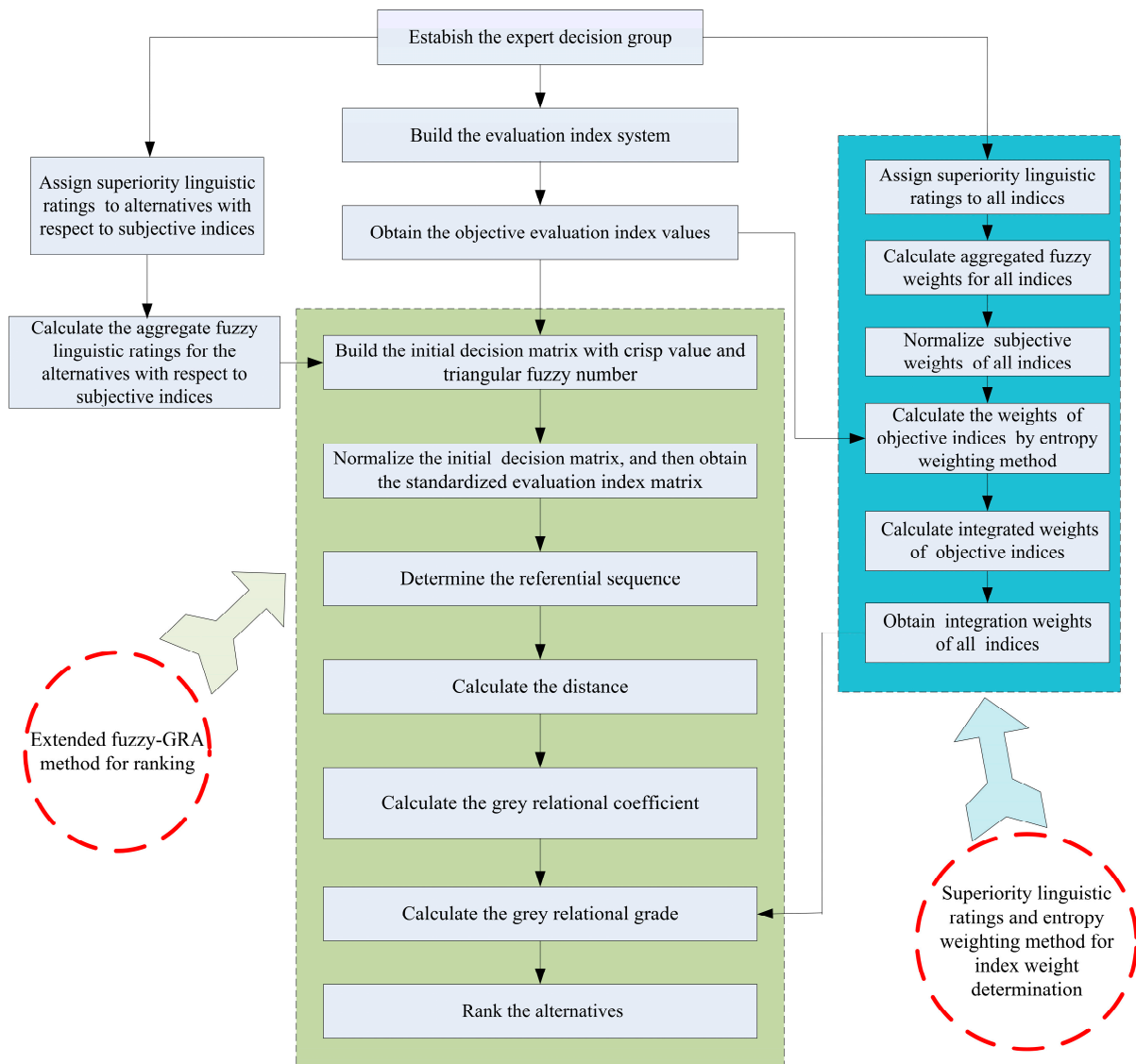


Figure 2. Calculation framework of the hybrid MCDM approach for external benefit evaluation of renewable energy power in China.

5. External Benefit Evaluation of Renewable Energy Power in China

In this section, the hybrid MCDM method is employed to evaluate the external benefit of renewable energy power in China. In a regional electric power system, there are 13 conventional thermal power units with 3080 MW of installed capacity, 6 wind farms with 345 MW of installed capacity, 8 solar photovoltaic power plants with 66.6 MW of installed capacity, and 6 biomass power plants with 91 MW of installed capacity. The total installed capacity of this electric power system amounts to 3582.6 MW, and the renewable energy power takes a 14.03% share in the total installed capacity. The average operating life of renewable energy power projects is 20 years. The parameters related to thermal power generation and renewable energy power generation, such as thermal power standard coal consumption, thermal power generation cost, equivalent forced outage rate, wind speed, lighting condition, biomass material supply shortage probability and so on, can refer to [47,48].

According to the previous studies of our research team [47–49], the objective evaluation index values can be obtained, which are listed in Table 4.

Table 4. The objective evaluation index value [Units: RMB Yuan]

Index Alternative	I1	I2	I3	I6	I7	I9	I10	I11
Wind power	66,900,120	12,713,328	20,576,005	9,312,000	52,295,507	84,207,641	3,720,437	7,875,000
Solar PV power	13,017,902	1,553,992	460,943	3,312,000	11,667,544	10,292,975	454,761	2933
Biomass power	19,517,562	9,222,004	1,290,020	3,408,000	45,449,956	30,541,304	1,079,494	2590

We selected four experts in different fields, also called decision makers ($j = 1, 2, 3, 4$) to provide the linguistic preference ratings for the alternatives and the indices according to Table 2 and Table 3. The specific calculation steps for employing the hybrid MCDM approach to evaluate the external benefit of renewable energy power are given below.

Step 1: Calculate the evaluation index weight

(1) Calculate the fuzzy subjective evaluation index weights

The fuzzy subjective weights of all indices based on the experts’ superiority linguistic ratings should first be calculated. Four decision makers provided the linguistic ratings for all indices and the results are given in Table 5. Then, the linguistic ratings can be transformed into the triangular fuzzy number according to Table 3. Finally, the aggregate fuzzy linguistic ratings for all indices can be calculated according to Equation (3). For example, the aggregated fuzzy weight \tilde{s}_1 of index I1 is computed as follows:

$$l_1^L = \frac{1}{4} \times (0.2 + 0 + 0 + 0.2) = 0.1; \quad l_1^M = \frac{1}{4} \times (0.5 + 0.3 + 0.3 + 0.5) = 0.4;$$

$$l_1^R = \frac{1}{4} \times (0.8 + 0.5 + 0.5 + 0.8) = 0.65$$

So, $\tilde{s}_1 = (l_1^L, l_1^M, l_1^R) = (0.1, 0.4, 0.65)$.

Table 5. Linguistic ratings for all indices.

	DM1	DM2	DM3	DM4
I1	M	L	L	M
I2	M	L	L	M
I3	M	M	L	H
I4	H	M	M	H
I5	H	H	M	H
I6	H	M	L	H
I7	L	L	L	M
I8	M	M	L	H
I9	H	M	H	H
I10	H	M	H	M
I11	M	M	H	M

Likewise, the aggregate fuzzy weights of the remaining ten indices can be computed, and the results are list in Table 6.

Table 6. Aggregate fuzzy weights of all indices.

Index	Aggregated fuzzy weight
I1	(0.1,0.4,0.65)
I2	(0.1,0.4,0.65)
I3	(0.225,0.5,0.775)
I4	(0.35,0.6,0.9)
I5	(0.425,0.65,0.95)
I6	(0.3,0.55,0.825)
I7	(0.05,0.35,0.575)
I8	(0.225,0.5,0.775)
I9	(0.425,0.65,0.95)
I10	(0.35,0.6,0.9)
I11	(0.275,0.55,0.85)

Then, the normalized subjective weights u_k of all indices based on the decision makers' superiority linguistic ratings can be calculated according to Equation (4), which are

$$u_1 = 0.06787, u_2 = 0.06787, u_3 = 0.08664, u_4 = 0.1054, u_5 = 0.1148$$

$$u_6 = 0.0960, u_7 = 0.0585, u_8 = 0.0866, u_9 = 0.1148, u_{10} = 0.1054$$

$$u_{11} = 0.0960$$

(2) Calculate the objective weights of objective indices by using entropy weighting method

For the objective index I1, I2, I3, I6, I7, I9, I10 and I11, the objective weights can be computed based on the index value (listed in Table 4) by using the entropy weighting method, and the calculation result are listed in Table 7.

Table 7. Objective weights of objective indices.

Index	I1	I2	I3	I6	I7	I9	I10	I11
Objective weight	0.0768	0.0685	0.2428	0.0399	0.0443	0.0881	0.0989	0.3406

(3) Calculate the integrated weight of all indices

The integrated weight z_k ($k = 1, 2, 3, 6, 7, 9, 10, 11$) of objective indices can be computed according to Equations (5) and (6), and the results are as follows,

$$z_1 = 0.0399, z_2 = 0.0358, z_3 = 0.1610, z_6 = 0.0294,$$

$$z_7 = 0.0198, z_9 = 0.0774, z_{10} = 0.0798, z_{11} = 0.2503$$

Then, the integration weights of all indices can be obtained according to Equation (7), as listed in Table 8.

Table 8. The integration weights of all indices by using superiority linguistic ratings and the entropy weighting method.

Index	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11
Integration weight	0.040	0.036	0.161	0.105	0.115	0.029	0.020	0.087	0.077	0.080	0.250

As listed in Table 8, it can be seen that I3 (electric power consumer expenditure increase), I4 (economic growth promotion degree), I5 (energy security enhancement degree) and I11 (bird and vegetation damage) have larger weights, which indicate these indicators will have greater impacts on the external benefit evaluation of renewable energy power in China. I8 (technical innovation promotion degree), I9 (environmental pollutant emission reduction) and I10 (water savings) will have medium impacts on the final evaluation, and the remaining indicators do not dominate.

Step 2: Calculate the aggregate fuzzy linguistic ratings for alternatives with respect to subjective indices

Four decision makers provided the linguistic ratings for the alternatives with respect to subjective indices, and the results are given in Table 9. Then, the linguistic ratings could be transformed as the triangular fuzzy number according to Table 2. Finally, the aggregate fuzzy linguistic ratings for the alternatives with respect to subjective indices (including I4, I5 and I8) could be calculated according to Equation (9). For example, the aggregate fuzzy rating of wind power in term of index I4 is computed as follows:

$$a_{14}^L = \frac{1}{4} \times (0.3 + 0.6 + 0.6 + 0.6) = 0.525; \quad a_{14}^M = \frac{1}{4} \times (0.5 + 0.8 + 0.8 + 0.8) = 0.725;$$

$$a_{14}^R = \frac{1}{4} \times (0.7 + 1 + 1 + 1) = 0.925$$

So, $\tilde{a}_{14} = (0.525, 0.725, 0.925)$.

Table 9. Linguistic ratings for renewable energy power with respect to subjective indices.

	DM1	DM2	DM3	DM4
(I4)				
wind power	F	G	G	G
PV power	F	F	G	F
bomass power	F	P	F	P
(I5)				
wind power	G	G	F	F
PV power	G	G	F	F
bomass power	F	G	F	P
(I8)				
wind power	G	F	F	P
PV power	G	F	G	G
bomass power	F	F	F	VP

Likewise, the aggregate fuzzy ratings of PV power and biomass power in term of indices I5 and I8 can be computed. The aggregate fuzzy ratings of renewable energy power with respect to subjective indices are presented in Table 10.

Table 10. Aggregate fuzzy ratings of renewable energy power with respect to subjective indices.

Index Alternatives	I4	I5	I8
wind power	(0.525,0.725,0.925)	(0.45,0.65,0.85)	(0.3,0.5,0.7)
PV power	(0.375,0.575,0.775)	(0.45,0.65,0.85)	(0.525,0.725,0.925)
bomass power	(0.15,0.35,0.55)	(0.3,0.5,0.7)	(0.225,0.375,0.575)

Step 3: Build the initial hybrid decision matrix

According to Tables 4 and 10, the initial hybrid decision matrix *A* which includes crisp values and triangular fuzzy numbers can be obtained:

$$A = \begin{bmatrix} 66900120 & 12713328 & 20576005 & (0.525,0.725,0.925) & (0.45,0.65,0.85) & 9312000 & 52295507 & (0.3,0.5,0.7) & 84207641 & 3720437 & 7875000 \\ 13017902 & 1553992 & 460943 & (0.375,0.575,0.775) & (0.45,0.65,0.85) & 3312000 & 11667544 & (0.525,0.725,0.925) & 10292975 & 454761 & 2933 \\ 19517562 & 9222004 & 1290020 & (0.15,0.35,0.55) & (0.3,0.5,0.7) & 3408000 & 45449956 & (0.225,0.375,0.575) & 30541304 & 1079494 & 2590 \end{bmatrix}$$

Step 4: Standardize the initial hybrid decision matrix

In the external benefit evaluation index system of renewable energy power, the index need to be normalized. According to Equations (10)–(13), we can get the normalized hybrid evaluation index matrix *B* with crisp values and triangular fuzzy numbers, as follows:

$$B = \begin{bmatrix} 0.1045 & 0.0947 & 0.0162 & (0.5676,0.7839,1) & (0.5294,0.7647,1) & 0.5808 & 0.4780 & (0.3243,0.5405,0.7568) & 0.6734 & 0.7080 & 0.0002 \\ 0.5372 & 0.7747 & 0.7248 & (0.4054,0.6216,0.8378) & (0.5294,0.7647,1) & 0.2066 & 0.1066 & (0.5676,0.7838,1) & 0.0823 & 0.0865 & 0.4689 \\ 0.3583 & 0.1306 & 0.2590 & (0.1622,0.3784,0.5946) & (0.3529,0.5882,0.8235) & 0.2126 & 0.4154 & (0.2432,0.4054,0.6216) & 0.2442 & 0.2054 & 0.5310 \end{bmatrix}$$

Step 5: Determine the referential sequence

The referential sequence *B*₀ with crisp values and triangular fuzzy numbers can be calculated according to Equation (15), and the result is as follows:

$$B_0 = [0.5372 \quad 0.7747 \quad 0.7248 \quad (0.5676,0.7839,1) \quad (0.5294,0.7647,1) \quad 0.5808 \quad 0.4780 \quad (0.5676,0.7838,1) \quad 0.6734 \quad 0.7080 \quad 0.5310]$$

Step 6: Calculate the distance

The distances between referential sequence *B*₀ and alternative sequences (wind power, PV power and biomass power) with respect to total 11 indicators can be separately calculated according to Equation (17), and the results are listed in Table 11.

Table 11. The distances between referential sequence B_0 and alternative sequences with respect to all indices.

	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11
Wind power	0.433	0.680	0.709	0.000	0.000	0.000	0.000	0.243	0.000	0.000	0.531
PV power	0.000	0.000	0.000	0.162	0.000	0.374	0.371	0.000	0.591	0.621	0.062
Biomass power	0.179	0.644	0.466	0.405	0.176	0.368	0.063	0.366	0.429	0.503	0.000

Step 7: Calculate the Grey relational coefficient

The grey relational coefficient of alternatives (wind power, PV power and biomass power) from the ideal one with respect to each index can be calculated according to Equation (18), and the results are listed in Table 12.

Table 12. Grey relational coefficient of alternatives from the ideal one with respect to each index.

	I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11
Wind power	0.450	0.343	0.333	1.000	1.000	1.000	1.000	0.593	1.000	1.000	0.400
PV power	1.000	1.000	1.000	0.686	1.000	0.486	0.488	1.000	0.375	0.363	0.851
Biomass power	0.664	0.355	0.432	0.466	0.668	0.490	0.850	0.492	0.452	0.413	1.000

Step 8: Calculate the Grey relational grade

The Grey relational grade of alternatives (wind power, PV power and biomass power) from the ideal one can be calculated according to Equation (19), which are as followings.

$$\gamma(B_0, B_1)=0.66198, \quad \gamma(B_0, B_2)=0.80511, \quad \gamma(B_0, B_3)=0.62666$$

The calculation result shows the external benefit ranking of renewable energy power is $PV \text{ power} \succ wind \text{ power} \succ biomass \text{ power}$. Therefore, we can draw the conclusion that PV power has the greatest external benefit, the second is wind power, and the external benefit of biomass power is minimal.

6. Conclusions

In this paper, the external benefits of three renewable energy power types (wind power, solar PV power and biomass power) in China are evaluated. The main conclusions are as follows.

- (1) After analyzing the impacts of renewable energy power accessing the power grid on conventional power generation enterprises, power grid companies, electric power consumers and the environment as well as society, the external benefit evaluation index system for renewable energy power in China was built from economic, social and environmental factor based on the concept of sustainability, using 11 indicators: power grid company revenue reduction, power generation enterprise cost increase, electric power consumer expenditure increase, economic growth promotion degree, energy security enhancement degree, employment

- increase, fiscal tax increase, technical innovation promotion degree, environmental pollutant emission reduction, water savings and bird and vegetation damage.
- (2) Superiority linguistic ratings and the entropy weighting method for index weight determination and extended fuzzy Grey relation analysis for alternative ranking, which includes crisp values and triangular fuzzy numbers, were discussed in detail, and the evaluation's result demonstrates this hybrid MCDM approach (the combination of superiority linguistic ratings, entropy weighting method and extended fuzzy-GRA) is effective and practical.
 - (3) The external benefit evaluation of renewable energy power in a regional electric power system indicates that solar PV power has the maximum external benefit, followed by wind power and biomass power.

Renewable energy power in China has developed rapidly since the implementation of the "Renewable Energy Law" in 2006, especially wind power, the cumulative installed capacity of which has exceeded that of USA in 2010 and ranks first in the world. However, wind power and PV power only accounted for 2.5% and 0.17% of total electricity power generation in 2013, respectively. To achieve the development goal of a 15% share in the total energy consumption for renewable energy, the Chinese government needs to formulate a reasonable plan for renewable energy and renewable energy power. Since 2006, the Chinese government has provided a large number of subsidies for renewable energy power development, including price subsidies for renewable energy power generation projects, subsidies for renewable energy power accessing-grid projects and subsidies for public independent power systems for renewable energy, which have had some positive benefits but also caused certain financial burdens [8]. In the past few years, China's wind power has developed very quickly and obtained the most government subsidies, but PV power and biomass power experienced a relatively slow development period. However, the rapid and blind construction of wind power without rational planning and consideration has caused a large percentage of wind power generation to be abandoned (11% at the national level and even 20.65% in Gansu province in 2013), which invalidates some government subsidies. Rational, balanced development planning and support policies for different renewable energy power types based on their comprehensive benefit impacts on different stakeholders in the electric power system should be focused on, to promote the healthy and sustainable development of the renewable energy power industry. Our study indicates that solar PV power should be paid more attention. Currently, more supporting policies for solar PV power development should be provided, such as providing financial support for research on solar energy conversion efficiency and PV technology, and striving to improve the current international trade pattern. Promoting the harmonious, balanced and sustainable development of renewable energy power not only helps to achieve that renewable energy development goal, making the most of the governmental renewable energy power subsidies, it can also reduce dependence on fossil fuels and improve the environment and air quality.

Acknowledgments

This study is supported by the Humanities and Social Science project of the Ministry of Education of China (Project number: 11YJA790217), the National Natural Science Foundation of China (Project

number: 71373076) and the Beijing Sino-foreign Joint Postgraduate Training Co-construction Project. Thank to Hongze Li and Bao Wang for proving parts of the data used in this paper.

Author Contributions

Huiru Zhao and Sen Guo built the evaluation index system and hybrid fuzzy MCDM method and performed the experiments together. Sen Guo completed the paper. All authors have read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. Brundtland, G.H. *Report of the World Commission on Environment and Development: Our Common Future*; United Nations: New York, NY, USA, 1987.
2. Li, X.; Pan, J. *China Green Development Index Report 2011*; Springer-Verlag: Berlin, Germany, 2012.
3. Dincer, I. Renewable energy and sustainable development: A crucial review. *Renew. Sustain. Energy Rev.* **2000**, *4*, 157–175.
4. Lund, H. Renewable energy strategies for sustainable development. *Energy* **2007**, *32*, 912–919.
5. British Petroleum. BP Statistical Review of World Energy 2014. Available online: <http://www.bp.com/content/dam/bp/pdf/Energy-economics/statistical-review-2014/BP-statistical-review-of-world-energy-2014-full-report.pdf> (accessed on 9 April 2015).
6. Shen, J.; Luo, C. Overall review of renewable energy subsidy policies in China—Contradictions of intentions and effects. *Renew. Sustain. Energy Rev.* **2015**, *41*, 1478–1488.
7. Lo, K. A critical review of China's rapidly developing renewable energy and energy efficiency policies. *Renew. Sustain. Energy Rev.* **2014**, *29*, 508–516.
8. Zhao, H.; Guo, S.; Fu, L. Review on the costs and benefits of renewable energy power subsidy in China. *Renew. Sustain. Energy Rev.* **2014**, *37*, 538–549.
9. Zeng, M.; Liu, X.; Li, Y.; Peng, L. Review of renewable energy investment and financing in China: Status, mode, issues and countermeasures. *Renew. Sustain. Energy Rev.* **2014**, *31*, 23–37.
10. Aslani, A.; Wong, K.F.V. Analysis of renewable energy development to power generation in the United States. *Renew. Energy* **2014**, *63*, 153–161.
11. Delarue, E.D.; Luickx, P.J.; D'haeseleer, W.D. The actual effect of wind power on overall electricity generation costs and CO₂ emissions. *Energy Convers. Manag.* **2009**, *50*, 1450–1456.
12. Holttinen, H.; Tuhkanen, S. The effect of wind power on CO₂ abatement in the Nordic Countries. *Energy Policy* **2004**, *32*, 1639–1652.
13. Ummels, B.C.; Gibescu, M.; Pelgrum, E.; Kling, W.L.; Brand, A.J. Impacts of wind power on thermal generation unit commitment and dispatch. *IEEE Trans. Energy Convers.* **2007**, *22*, 44–51.
14. Hirth, L. The market value of variable renewables: The effect of solar wind power variability on their relative price. *Energy Econ.* **2013**, *38*, 218–236.

15. Keith, D.W.; DeCarolis, J.F.; Denkenberger, D.C.; Lenschow, D.H.; Makyshev, S.L.; Pacala, S.; Rasch, P.J. The influence of large-scale wind power on global climate. *Proc. Natl. Acad. Sci. USA* **2004**, *101*, 16115–16120.
16. Morales, J.M.; Conejo, A.J.; Pérez-Ruiz, J. Economic valuation of reserves in power systems with high penetration of wind power. *IEEE Trans. Power Syst.* **2009**, *24*, 900–910.
17. Delucchi, M.A.; Jacobson, M.Z. Providing all global energy with wind, water, and solar power, Part II: Reliability, system and transmission costs, and policies. *Energy Policy* **2011**, *39*, 1170–1190.
18. Katzenstein, W.; Apt, J. Air emissions due to wind and solar power. *Environ. Sci. Technol.* **2008**, *43*, 253–258.
19. Turney, D.; Fthenakis, V. Environmental impacts from the installation and operation of large-scale solar power plants. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3261–3270.
20. Heller, M.C.; Keoleian, G.A.; Mann, M.K.; Volk, T.A. Life cycle energy and environmental benefits of generating electricity from willow biomass. *Renew. Energy* **2004**, *29*, 1023–1042.
21. Santisirisomboon, J.; Limmeechokchai, B.; Chungpaibulpatana, S. Impacts of biomass power generation and CO₂ taxation on electricity generation expansion planning and environmental emissions. *Energy Policy* **2001**, *29*, 975–985.
22. Wang, Y.M.; Elhag, T.M.S. Fuzzy TOPSIS method based on alpha level sets with an application to bridge risk assessment. *Expert Syst. Appl.* **2006**, *31*, 309–319.
23. Zhao, H.; Guo, S. Selecting green supplier of thermal power equipment by using a hybrid MCDM method for sustainability. *Sustainability* **2014**, *6*, 217–235.
24. Opricovic, S. Fuzzy VIKOR with an application to water resources planning. *Expert Syst. Appl.* **2011**, *38*, 12983–12990.
25. Kim, Y.; Chung, E.S. Fuzzy VIKOR approach for assessing the vulnerability of the water supply to climate change and variability in South Korea. *Appl. Math. Modell.* **2013**, *37*, 9419–9430.
26. Hatami-Marbini, A.; Tavana, M. An extension of the Electre I method for group decision-making under a fuzzy environment. *Omega* **2011**, *39*, 373–386.
27. Vahdani, B.; Hadipour, H. Extension of the ELECTRE method based on interval-valued fuzzy sets. *Soft Comput.* **2011**, *15*, 569–579.
28. Liao, M.S.; Liang, G.S.; Chen, C.Y. Fuzzy grey relation method for multiple criteria decision-making problems. *Qual. Quant.* **2013**, *47*, 3065–3077.
29. Goyal, S.; Grover, S. Applying fuzzy grey relational analysis for ranking the advanced manufacturing systems. *Grey Syst. Theory Appl.* **2012**, *2*, 284–298.
30. Wei, G.W. GRA method for multiple attribute decision making with incomplete weight information in intuitionistic fuzzy setting. *Knowl.-Based Syst.* **2010**, *23*, 243–247.
31. Kuo, M.S.; Liang, G.S. Combining VIKOR with GRA techniques to evaluate service quality of airports under fuzzy environment. *Expert Syst. Appl.* **2011**, *38*, 1304–1312.
32. Zhang, S.; Liu, S.; Zhai, R. An extended GRA method for MCDM with interval-valued triangular fuzzy assessments and unknown weights. *Comput. Ind. Eng.* **2011**, *61*, 1336–1341.
33. Hirth, L. The optimal share of variable renewables: How the variability of wind and solar power affects their welfare-optimal deployment. *Energy J.* **2015**, *36*, 127–162.

34. Broeer, T.; Fuller, J.; Tuffner, F.; Chassin, D.; Djilali, N. Modeling framework and validation of a smart grid and demand response system for wind power integration. *Appl. Energy* **2014**, *113*, 199–207.
35. Haaren, R.; Morjaria, M.; Fthenakis, V. Empirical assessment of short-term variability from utility-scale solar PV plants. *Prog. Photovolt.* **2014**, *22*, 548–559.
36. Zhang, Q.; Zhou, D.; Fang, X. Analysis on the policies of biomass power generation in China. *Renew. Sustain. Energy Rev.* **2014**, *32*, 926–935.
37. Singh, M.; Khadkikar, V.; Chandra, A.; Varma, R.K. Grid interconnection of renewable energy sources at the distribution level with power-quality improvement features. *IEEE Trans. Power Deliv.* **2011**, *26*, 307–315.
38. Schuman, S.; Lin, A. China's renewable energy law and its impact on renewable power in China: progress, challenges and recommendations for improving implementation. *Energy Policy* **2012**, *51*, 89–109.
39. Zadeh, L.A. Fuzzy sets. *Inf. Control* **1965**, *8*, 338–353.
40. Chen, S.H.; Hsieh, C.H. Representation, ranking, distance, and similarity of L-R type fuzzy number and application. *Aust. J. Intell. Process. Syst.* **2000**, *6*, 217–229.
41. Wang, Q.; Wu, C.; Sun, Y. Evaluating corporate social responsibility of airlines using entropy weight and grey relation analysis. *J. Air Transp. Manag.* **2015**, *42*, 55–62.
42. Li, L.; Liu, F.; Li, C. Customer satisfaction evaluation method for customized product development using Entropy weight and Analytic Hierarchy Process. *Comput. Ind. Eng.* **2014**, *77*, 80–87.
43. Wei, G. Grey relational analysis model for dynamic hybrid multiple attribute decision making. *Knowl.-Based Syst.* **2011**, *24*, 672–679.
44. Wang, Y.; Xi, C.; Zhang, S.; Yu, D.; Zhang, W.; Li, Y. A combination of extended fuzzy AHP and fuzzy GRA for government E-tendering in hybrid fuzzy environment. *Sci. World J.* **2014**, *2014*, doi:10.1155/2014/123675.
45. Liu, S.; Dang, Y.; Fang, Z.; Xie, N. *Grey System Theory and its Application*; Science Press: Beijing, China, 2010.
46. Deng, J.L. Introduction to grey systems. *J. Grey Syst.* **1989**, *1*, 1–24.
47. Li, H.; Zhao, H.; Wang, B.; Guo, S. External value estimation of on-grid wind power. *Mod. Electr.* **2012**, *29*, 83–88.
48. Wang, B. Research on Externality Assessment Model and Countermeasures of Renewable Energy Power Generation. Master's Thesis, North China Electric Power University, Beijing, China, June 2013.
49. Guo, S. Research on the Compensation Mechanism of Grid-Connected Renewable Energy Power Generation. Master's Thesis, North China Electric Power University, Beijing, China, June 2013.