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Evaluation of different types of alternative energy sources in China using hybrid methods

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Abstract. In recent years, alternative energy sources(AES) including hydropower, wind power, nuclear energy, solar power, and biomass are becoming increasingly popular in China. Comprehensive evaluation of each AES is of vital importance for the further development of energy production and utilization. This study combines the Life-Cycle Assessment (LCA) with Multi-Criteria Decision-Making(MCDM) methods and assesses AES in China comprehensively. The results show that hydropower is the best AES in China. However, the study cannot rank the rest of the AES because different evaluation criteria weights and different MCDM methods lead to different results for the AES ranking. By analyzing China's policies, the technical aspect should be considered first, following environmental factors, economic feasibility, and social sustainability. There are several limitations of evaluation methods and more studies need to be done.

Keywords: Alternative Energy Source(AES), Multi-Criteria Decision-Making(MCDM), Life-Cycle Assessment(LCA), renewable energy source, China's policies.

1. Introduction

In recent years, society has raised awareness of energy use issues. The substantial use of conventional energy sources, such as coal, natural gas, and petroleum, causes a series of global problems: air pollution and climate change. China has become one of the countries that produce the most carbon dioxide. To reduce carbon emissions, alternative energy sources(AES) gradually replace the role of conventional energy sources in energy production and consumption. AES include hydropower, wind power, nuclear energy, solar power, and biomass. These five types of AES show very good prospects for development and utilization since they significantly reduce greenhouse gas emissions compared with conventional energy sources[1]. However, this does not mean that they don't cause any damage to the environment. Each of these five AES contains its own advantages as well as disadvantages, which should be evaluated well before utilizing them. Several vital factors including the environment, technology, economy, and politics should be considered to comprehensively assess each AES. This study mainly focuses on two specific questions:

1. How to objectively evaluate different types of AES from various aspects using different methods?
2. Which type of AES is the most suitable for current environmental situations and China's policies?

Currently, there are several methods and models that help assess AES from different aspects. This study will mainly focus on two methods: Life Cycle Assessment(LCA) technique, which considers the

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impacts of industrial processes on the environment at various stages of the life cycle, and Multi-Criteria Decision-Making(MCDM) techniques, which assess each AES using evaluation criteria and sub-criteria[5].

This study aims to combine these evaluation methods, figure out a hybrid method that can be applied to assess AES from different aspects, and further develop energy technologies according to the evaluation results.

2. Research methodology

2.1. Life Cycle Assessment

Life Cycle Assessment(LCA) technique considers the potential environmental impacts quantitatively from various stages of life cycles, including manufacturing, constructing, operating, and decommissioning[1]. Different AES contain different details of each stage of life cycle. And at the same stage of life cycle, each AES influences the environment differently due to the different natures and processing methods. Assessing the environmental impacts at each stage of life cycle helps understand how much each AES influences the environment at each stage. Wang et. al. mention several life cycle impact assessment indicators: global warming potential(CO_2-eq), photochemical ozone creation potential(C_2H_4-eq), eutrophication potential(PO_4^{3-}eq), acidification potential (SO_2-eq), and human toxicity potential(1,4-DB-eq)[1]. These indicators are harmful gases that cause serious environmental problems. Turconi et. al. also include nitrogen oxides(labeled NO_x) as an indicator[2]. These indicators are usually calculated in the unit "g/kWh"(grams of gas produced per kilowatt-hour of energy consumption). Several studies use different units like "mg/kWh", so this study converts them to the same unit "g/kWh"[2]. An advantage of LCA is that it assesses environmental impacts quantitatively using different indicators. However, it partially ignores other potential environmental impacts. High noise level(sound pollution), visual impact, and the potential influences on terrestrial and marine life are also environmental impacts, which LCA fails to consider[3]. Another limitation is that LCA technique only assesses environmental factors. In real-life situations, other factors should be considered: social acceptance, economic problems, technical issues, and policies[4]. It is not appropriate to only use this single-target analysis technique[3].

2.2. Multi-Criteria Decision Making

Multi-Criteria Decision Making(MCDM) techniques assess each AES using multiple actors, criteria, and objectives[4]. MCDM is an umbrella terminology that describes the core of the evaluation techniques. There are many models of MCDM, including Analytic Hierarchy Process(AHP) and VlseKriterijumska Optimizacija I Kompromisno Resenje(VIKOR)[4]. In addition, there are other specific techniques that enhance the accuracy of evaluation. Wu et. al. apply cumulative prospect theory, which helps eliminate the assumption that investors in the of energy industry always make rational choices. Table 1 lists some of the common MDCM methods and other techniques. But these models and techniques are so complicated that this study will not apply all the models to assess AES. This study pays attention to the evaluation criteria and sub-criteria, the specific factors that can be used to assess AES from different aspects. First, there are five main criteria: social sustainability; environmental factors; economic feasibility; technical aspects, and policies[5]. For each criterion, there are sub-criteria. For instance, social sustainability can be divided into employment creation, public acceptance, and social benefits[5]. Environmental factors encompass land requirements, greenhouse gas emissions, and other potential environmental impacts. Table 2 shows the MCDM evaluation criteria and sub-criteria. The main advantage of MCDM techniques is that they consider AES from different aspects. This makes the evaluation more comprehensive and accurate. It would be better if LCA and MCDM can be hybridized. LCA assesses each AES at four different stages of life cycles, so it better reflects the impacts of harmful gases on the environment. Adding the indicators of LCA to MCDM's "sub-criteria" enhances the accuracy of the evaluation results of the potential environmental impacts. In this way, the two

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methods are hybridized. This study will integrate data from different studies to assess each AES from different evaluation criteria and sub-criteria.

Table 1. Several MCDM methods and other techniques.

MDCM Method	Description
Analytic Hierarchy Process (AHP)	It determines a goal and list criteria and sub-criteria in hierarchy[5].
Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS)	The best choice should be the closest to the positive-ideal solution and the farthest to the negative-ideal solution[6].
VlseKriterijumska Optimizacija I Kompromisno Resenje(VIKOR)	Compromise ranking is performed by comparing the measure of closeness to the ideal solution[6].
Technique	Description
Fuzzy Set Theory	It deals with uncertainties when making decisions[5].
Cumulative Prospect Theory	It eliminates the assumption that investors of energy industry always do rational choices[5].

Table 2. Common MCDM evaluation criteria and sub-criteria.

Evaluation Criteria	Sub-Criteria	Reference(s)
Social Sustainability	Employment Creation	[3,5,6]
	Public Acceptance	[3,5,6,7]
	Social Benefits	[3,5,6]
Environmental Factors	Land / Area Requirements	[3,5,6]
	Renewable or not?	/
	Potential Impacts	[3]
	Global Warming Potential	[1,2,3]
	Acidification Potential	[1,2]
	Eutrophication Potential	[1]
	Photochemical Ozone Creation Potential	[1]
	Human Toxicity Potential	[1]
	Nitric Oxides Production	[2]
Economic Feasibility	Capital Lost	[5]
	Operations and Maintenance	[5]
	Electricity Cost	[5]
	Payback Period	[5]
	Profitability / Potential Market (in China)	/
Technical Aspect	Maturity	[5]
	Reliability	[5]
	Efficiency	[5]
	Resource Availability	[5]
Policies	Policies in China	/

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3. Current situations of AES in China

Currently, China's most prominent alternative energy technologies are hydropower, wind power, solar power, nuclear power, and biomass. Renewable energy sources(five AES except nuclear power) in China account for about 17% of the global total in 2016, which means China has been one of the most developed areas of energy development in the world[5]. Each AES has its own development situation.

Hydropower, using falling or fast-running water to produce power, is considered one of the most reliable and mature renewable energy source in China[8]. China has very rich hydro resources and huge hydropower potential, with a total of about 694 GW[5]. There are more than 90,000 reservoirs, among which the largest is the Three Gorges which is situated along the Yangtze River[8]. However, ongoing problems include limited memory usage, long execution time, and uneven spatial distribution of resources[8].

Wind Power is ranked second in the development of renewable energy technologies in China[5]. By the middle of 2015, China's wind power's installed capacity cumulatively reached about 125 GW[9]. Nevertheless, wind power has faced curtailment due to the far distance from the resources to the load center[5]. There are also problems with blind investment in noneconomic operations[9].

Solar technologies convert the energy of sunlight into useful energy sources. Solar energy is comprised of solar thermal energy and solar photovoltaic(PV). Solar PV is applied by converting sunlight energy into electricity, while solar thermal converts solar energy into heat[10]. Overall, solar technologies show great potential for development. But there are also obstacles: the technologies are still immature and there are serious pollution problems[5].

Most studies on the evaluation of energy sources using LCA and MCDM methods do not consider nuclear power. Even though it is not a type of renewable energy source, it is a type of AES. This study will include nuclear power as an evaluation subject and give a brief analysis. Biomass is derived from organic substance[6]. China is rich in biomass resources[5]. However, biomass technology has not been highly encouraged by China's government until recent years. This may be due to high raw material expenses and a lack of core technology[5].

4. Discussion

4.1. Analysis of the ranking results

Most studies focus on electricity production or heat technologies to assess each AES[11]. For most studies, the MCDM analysis has several procedures: defining a system with objectives; finding all the criteria affecting system based on objectives; seeking alternative systems; setting weights to alternatives; selecting an MCDM method for the purpose; presenting an optimal alternative for evaluation[4]. Table 3 shows the evaluation criteria and sub-criteria and specific data. The real analysis procedures are more complicated.

Table 3. Evaluation criteria and sub-criteria and the specific data from different studies.

("ND" means no data; "-" means no unit; "/" means no reference(s); *"Solar power" composes of solar photovoltaic(PV) and solar thermal energy. The data show the combination of two.)

Assessment Aspects	Specific Considerations	Unit	Hydropower	Wind Power	Solar Power *	Biomass	Nuclear Power	Reference
Social Sustainability	employment Creation	jobs/MW	0.9-1.2	0.9-4.0	0.2-25	11.2-19.7	ND	[3,5]
	Public Acceptance	—	0.0641	0.1750	0.3667	0.3667	0.0275	[12]
Environmental Factors	Land / Area Requirements	km2/GW	750	100-120	15-42	5000	small	[5]
	Renewable or not?	-	Yes	Yes	Yes	Yes	No	/
	Potential Impacts	-	/	/	/	/	/	[3,13]

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Table 3. (continued).

	Global Warming Potential (CO_2-eq)	g/kWh	3-4	26-27	ND	ND	12-13	[1,2,3]
	Acidification Potential (SO_2-eq)	g/kWh	0.02	0.2	ND	ND	0.12-0.13	[1,2]
	Eutrophication Potential (PO_4^{3-}-eq)	g/kWh	6-7	93-95	ND	ND	10-12	[1]
	Photochemical Ozone Creation Potential (C_2H_4-eq)	g/kWh	2	16	ND	ND	4-5	[1]
	Human Toxicity Potential (1,4-DB-eq)	g/kWh	5	31-32	ND	ND	2-4	[1]
	Nitric Oxides Production (NOx-eq)	g/kWh	0.04-0.06	0.11	0.20-0.40	0.08-1.7	0.01-0.04	[2]
Economic Feasibility	Capital Cost	USD/kW	1000-3500	950-1250	1150-7150	2000-2500	ND	[5]
	Operations and Maintenance	USD/kWa	45-52	17.31-31	12-70	63.8-84.7	ND	[5]
	Electricity Cost	USD/kWh	0.25	0.52	0.33-3.5	0.56-0.84	ND	[5]
	Payback Period	Year	5-10	13-16	7-13	6-9.5	ND	[5]
Technical Aspect	Maturity	-	0.5278	0.1059	0.1059	0.0556	0.2048	[12]
	Reliability	-	0.4849	0.1007	0.0691	0.2922	0.0531	[12]
	Efficiency	%	80	35	9.5-21	25-50	ND	[5]
	Resource Availability	Kwh/m2/year	1100	570	2130-2200	200	ND	[5]
Policies	Note: Studies should consider a country's policies to assess the development of alternative energy sources							/

4.1.1. Evaluation criteria weights. This study has discussed various evaluation criteria and sub-criteria, but they should be weighted differently according to the relative significance of each criterion. Wu et. al. use the fundamental "1-9 scale" created by Satty to compute the criteria and sub-criteria weights and get the weight of technology 0.37, economy 0.28, environment 0.23, and social 0.12[5]. Table 4 shows the criteria weights ranking of other studies. Most studies consider the technical aspects the highest weight, followed by economic, environmental, and social factors. A few studies rank economic feasibility as the most important criterion. All the studies in the table rank environmental factors second to last and social sustainability last. The conclusion is that technical and economic factors are the two most vital evaluation criteria.

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Table 4. Criteria weights ranking and evaluation results from different studies.

(*some studies include "geothermal energy", but this study will not analyze geothermal energy)

Number	Main Research Methodology	Case Study Region	Criteria Weights	Ranking of Alternative Energy Sources	Source
1	LCA	Mainland China	No need of calculations	Hydro > Nuclear Power > Wind	[1]
2	Fuzzy MCDM (IVHF-ELECTRE II)	Mainland China	Technical > Economic > Environmental > Social	Hydro > Wind > Solar PV > Biomass > Solar Thermal	[3]
3	Fuzzy MCDM Cumulative prospect theory	Mainland China	Economic > Technical > Environmental > Social	Solar PV > Hydro > Solar Thermal > Wind > Biomass	[5]
4	WSM	Taiwan	Technical > Economic > Environmental > Social	Hydro > Solar PV > Wind > Biomass > Geothermal*	[6]
5	TOPSIS	Taiwan		Hydro > Solar PV > Wind > Geothermal* > Biomass	[6]
6	VIKOR	Taiwan		Hydro > Wind > Solar PV > Biomass > Geothermal*	[6]
7	ELECTRE	Taiwan		Hydro > Solar PV > Wind > Geothermal* > Biomass	[6]
8	AHP	Mainland China	Technical > Economic > Environmental > Social	Hydro > Wind > Biomass > Solar > Nuclear	[12]

4.1.2. Discrepancy due to different methods. MCDM contains lots of methods and techniques. Many studies apply different MCDM methods, which have different rules and formulas. Therefore, the data and ranking results gained from each study are totally different. For instance, Wu et. al. apply fuzzy MCDM with the use of cumulative prospect theory in China[5]. They get the ranking: solar PV; hydropower; solar thermal; wind power; biomass[5]. Nonetheless, also in China, Niu et. al. apply fuzzy MCDM based on IVHF-ELECTRE and conclude that hydropower is the best AES, followed by wind power, solar PV, biomass, and solar thermal[3]. Table 4 shows the ranking results from different MCDM methods. It is difficult to make a conclusion about the overall ranking of AES due to the discrepancy of each ranking result. For instance, study number 1 in Table 4 ranks wind power last, while study number 2 ranks wind power second. Some studies evaluate nuclear power and geothermal energy, while others don't. However, several obvious patterns can be found. Among eight rankings in the table, seven of them rank hydropower first and five of them rank biomass the last(this study doesn't consider "geothermal"). Therefore, this study concludes that overall hydropower is the best AES, and biomass may not be a great AES.

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4.2. China's policies and the development of AES

China has posed several laws and policies that facilitate the energy technological development. Firstly, the 2006 Renewable Energy Law claimed to promote the development of renewable energy technologies; protect the environment; realize economically and socially sustainable development[13]. Considering feed-in tariffs and tax incentives, the criterion weight of economic feasibility may decrease for wind power[9]. Secondly, the "13th Five-Year Electric Power Plan" has mentioned that besides wind power and solar power, hydropower development is a priority[8]. Since 2016, China has developed wind power and solar power and has achieved remarkable progress. Nuclear energy was not mentioned because it is not considered as a renewable energy source. Biomass was not a priority. These two policies indicate that China supports the development of hydropower, wind power, and solar power technologies. This fits the pattern that the criterion "technology" is weighted the greatest in most studies. Due to several financial support from China's government, the criterion "economic feasibility" can be weighted less. Thirdly, according to the latest policy, by 2030, China's carbon dioxide emissions will reach a peak and decline after stabilization. By 2060, China will achieve carbon neutrality and comprehensively establish a green, low-carbon, and circular economy. This conveys that environmental problems are being taken more seriously. Therefore, when assessing AES, the criterion "environmental factors" should be weighted greater. The overall ranking of evaluation criteria weights in China may be technology, environment, economy, and society. According to this ranking, China should either decrease its support for wind power technological development or deal with pollution from industrial processes since wind power influences the environment significantly[1]. Hydropower is still the best AES.

4.3. Limitations

Current studies of AES have several limitations. First, the measurement data are usually not accurate. Real situations are unpredictable and uncontrollable. Errors are inevitable. Second, lots of research on AES focus on specific geographical areas and ignore others. It is not accurate to generalize the results of case studies to all the locations in China. Further studies of AES are necessary. First, increasing the accuracy of data collections and mathematical computations helps assess AES more accurately. Also, each MCDM method has its advantages and weaknesses. Hybridizing MCDM methods helps make the ranking of AES and the evaluation results more accurate. Further studies can focus on combining MCDM methods with other techniques or models to expand the evaluation criteria. Finally, further studies can consider more about politics and laws. Many current studies assess AES and aim to restructure the policies and laws. More studies can pay more attention to current policies and laws and, according to them, make a plan for energy development.

5. Conclusions

This study focuses on evaluation criteria and sub-criteria, combines LCA with MCDM, and uses this hybrid method to assess AES. However, different studies apply different MCDM methods and gain different results. Most studies rank technology first among criteria weights, followed by the economy, environment, and society. By analyzing China's policy on environmental protection, the criteria for environmental protection should be weighted more. Therefore, criteria weights ranking in China should be technology, environment, economy, and society. In many studies, the evaluation results show that hydropower ranks first and biomass ranks last among all AES. The rankings of the other AES vary in different studies. According to China's policies, hydropower is the priority for development. Solar power and wind power rank second and third place, respectively. This study shows several limitations. Current analysis processes are based on the data from other studies, while there is no further analysis of the real data. Future studies will collect actual data and do the comparative analysis more in-depth.

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