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EVALUATION INDEX SYSTEM FOR PERFORMANCE EVALUATION OF ECO-INDUSTRIAL THERMAL POWER PLANTS BY USING FUZZY DELPHI METHOD

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ABSTRACT

In order to promote the clean and sustainable production of coal resources, more and more eco-industrial thermal power plants (ETPPs) are established in China. Considering it is a burgeoning industry, the performance evaluation and management of the eco-industrial thermal power plants is important to the construction and development. Therefore, a evaluation index system for eco-industrial thermal power plants is presented in this paper. Because eco-industrial thermal power plants performs many tasks that should be measured by multiple criteria and requirements, Delphi method are involved to select the evaluation criteria. Moreover, in order to tolerate vagueness and ambiguity of subjective judgment, fuzzy theory is combined with the Delphi method in evaluation criteria determination process. Firstly, the initial evaluation criater are established based on circular economy theory, and then the fuzzy Delphi method is used to selected the final criteria. Finally, the fianal evaluation criteria contains of "Economy development," "Energy utilization," "Refuse recycle," and "Pollutant emissions" four aspects and 13 sub-criteria. This study provides a comprehensive and effective method for evaluation criteria selection of eco-industrial thermal power plants and also innovates the utilization of fuzzy Delphi method.

KEYWORDS: Eco-industrial thermal power plants, circular economy, fuzzy theory, Delphi method, evalution criteria.

INTRODUCTION

China' economy has been maintaining a high speed of development over the past 30 years, and a large amount of electricity still needs to be supplied to meet the demands of social and economic development. Considering the dominance of coal resources in China, thermal power industry has been receiciving priority over other power generation ways. Nowadays, thermal power plants consumes abouts 60% of the total coal resource and produces about 70% of the total install capacity. However, considering the low efficiency and severe pollution of traditional thermal power industry, thus it suffers pressures from the "Thirteen five-year plan" and " Energy saving and emission reduction plan in Twelfth five-year". Moreover, the "Coal clean utilization action plan (2015-2020)" was promulgated to strengthen units updating, ultra-lower emissions and waste recycling of thermal power plants. So the "Circular economy development strategies and action plans" was provided to appeal to thermal power industry to develop more eco-industrial parks, so that reduce resource consumption and pollutant emissions of electricity industry in China. Therefore, in order to promote the energy saving and emission reduction of thermal power industry, eco-industrial thermal plants are viewed as an abatement option.

Based on the concept of circular and sustainable economy, eco-industrial thermal power plants can significantly improve energy efficiency and reduce emissions through three stages of "Reduce", "Reuse" and "Recycle". However, eco-industrial thermal power plants are still in the early stage of management and technological exploration in China. It will suffer with uncertainties from different aspects, such as technological feasibility, input-output efficiency, recycling efficiency and so on. Therefore, in order to promote the production and management of eco-industrial thermal power plants, it is essential to establish an index sytem that can comprehensively evaluate the performance of sustainable ETPPs. Such an index sytem would help managers understand the situation of each stage and create solutions for developing forthcoming strategies. Besides, this index sytem would also aid authorities in properly supervising the production status and guaranteeing the sustainable production of eco-industrial thermal power plants.

In this study, the circular economy concept is employed to determine the initial evaluation criteria for the performance of eco-industrial thermal power plants, which covers many perspectives, such as "Economy development," "Energy utilization," "Refuse recycle," and "Pollutant emissions". Therefore, the initial criteria based on the circular economy theory can comprehensively measure and improve the sustainable performance of eco-industrial thermal power plants. Furthermore, to determine the final criteria for performance evaluation of eco-industrial thermal power plants, the fuzzy Delphi method (FDM) is introduced in this paper. Fuzzy Delphi method (FDM) is a group technique through a series of intensive questionnaires with controllable opinion feedback. It has been used to analyze and determine factors in various fields, such as economy management, ecology, production and so on. Moreover, this method can yield the most reliable consensus opinion about the evaluation criteria and overcome the problems of ambiguity and uncertainty in experts' responses. Therefore, the fuzzy Delphi method is used in this paper to effectively determine the final criteria for performance evaluation of eco-industrial thermal power plants, which innovates the application of this method.

The remainder of this paper is organized as follows: In Section 2, the basic theories of fuzzy Delphi method is elaborated. The evaluation index system for performance evaluation of eco-industrial thermal power plants is established by FDM in Section 3. The Section 4 explain the meaning of evaluation criteria. Conclusions are drawn in the last section.

FUZZY DELPHI METHOD

In 1963, Dalky and Helmer proposed the Delphi method (DM), which is a technique used to obtain the most reliable consensus among a group of experts. It has been widely used in the field of decision making and making predictions. In this method, experts can receive feedback and constantly modify and improve their previous opinions through several rounds of consulting. However, although this is a valuable and practical investigation and analysis tool, the traditional Delphi method is consuming and difficult to converge through repetitive surveys. Moreover, the most important thing is this method can not handle ambiguity and uncertainty in the responses of expert surveys. In order to solve the above deficiencies, the traditional Delphi method and fuzzy logic theory are combined. In the improved fuzzy Delphi method, experts express their opinions with three-point estimates by using triangular fuzzy numbers(TFNs). And the membership degree functions can represent expert's opinion, and the experts are not needed to improve their opinions again and again as the traditional Delphi method. Moreover, there is no useful information would be lost, since all opinions can be effectively taken into account through the membership function. Therefore, considering its advantages in investigation analysis and group decisions, various studies have embraced the fuzzy Delphi method to select and establish the evaluation criteria.To recognize the key criteria for the performance evaluation of eco-industrial thermal power plants, the FDM is introduced in this paper.

Essential steps of the FDM are listed as follows:

Step 1: Administer questionnaires and determine the most conservative value and the most optimistic value ranging from 0 to 10 for each criterion among a group of experts.

Step 2: Gather the minimum and maximum values reported by each expert for each criterion, and calculate the geometric mean accordingly. Then, compute the conservative TFN (C_L^i, C_M^i, C_U^i) and optimistic TFN (O_L^i, O_M^i, O_U^i) of each expert for each criterion, where C_L^i and O_L^i are the minimum remaining conservative value and minimum remaining optimistic value, respectively; C_U^i and O_U^i are the maximum remaining conservative value and maximum remaining optimistic value, respectively; and C_M^i and O_M^i are the geometric mean of the remaining conservative value and the geometric mean of the remaining optimistic value, respectively.

Step 3: Check that the expert opinions are consistent, and compute the value of the consensus significance G_i for each criterion (Jafari A et al. 2008).

(1) If $C_U^i \le O_L^i$, the criterion i holds consensus, and the value of the consensus significance G_i is computed by equation (1):

$$G_i = \frac{G_M^i + O_M^i}{2} \quad (1)$$

(2) If $C_U^i > O_L^i$, then the gray zone interval value ($Z^i = C_U^i - O_L^i$) is smaller than the interval value ($M^i = O_U^i - C_M^i$). Correspondingly, the value of the consensus significance is computed by equation (2):

$$G_i = \frac{\left[(C_U^i \times O_M^i) - (O_L^i \times C_M^i)\right]}{\left[\left[(C_U^i - C_M^i) + (O_M^i - O_L^i)\right]\right]} \quad (2)$$

When $C_U^i > O_L^i$, however, the gray zone interval value ($Z^i = C_U^i - O_L^i$) is greater than the interval value ($M^i = O_U^i - C_M^i$), which means that the expert opinions are inconsistent. Thus, steps 1-4 should be repeated until each criterion converges and the value of the consensus significance can be calculated (Jafari A et al. 2008).

ESTABLISH THE INDEX SYSTEM FOR PERFORMANCE EVALUATION OF ECO-INDUSTRIAL THERMAL POWER PLANTS

Energy saving and emission reduction data of thermal power plant.

Evaluation criteria are very important to the performance analysis and evaluation for eco-industrial thermal power plants. It is important to establish an evaluation index system to comprehensively reflect the inherent characteristics of eco-industrial thermal power plants. However, eco-industrial thermal power industry is still in the early stage of management and technological exploration, there is no consistent list of criteria for performance evaluation of eco-industrial thermal power plants in China. Since eco-industrial thermal power plants is a sustainable way of coal utilization, the evaluation index system for eco-industrial thermal power plants is built based on the concept of circular economy.Based on the concept of circular and sustainable economy, eco-industrial thermal power plants can significantly improve energy efficiency and reduce emissions through three stages of “Reduce”, “Reuse” and “Recycle”. Therefore, the evaluation index system for eco-industrial thermal power plants includes “Economy development” criteria, “Energy utilization” criteria, “Refuse recycle” criteria and “Pollutant emissions” criteria. Further, the sub-criteria that are affiliated with above four criteria are determined by fuzzy Delphi method as follows:

First of all, based on the circular economy theory, academic literatures and feasibility reports of eco-industrial thermal power plants, 32 initial sub-criteria are collected according to relative theories and expert consultation, in which “Economy development” criteria, “Energy utilization” criteria, “Refuse recycle” criteria and “Pollutant emissions” criteria are covered. Furthermore, the vital sub-criteria are selected as the final evaluation sub-criteria based on the FDM.

Experts firstly express their opinions on the sub-criteria importance through conservative and optimistic values. And the scores of sub-criteria lies on the scale from 0 to 10. Subsequently, according to Eqs. (1) and (2), the conservative TFN (C_L^i, C_M^i, C_U^i) and optimistic TFN (O_L^i, O_M^i, O_U^i) of each expert respect to each criterion are calculated, in Table 3. And then, the consistency of the experts’ opinions are verified by calculating the values of and . Finally, the vital sub-criteria are determined based on the consensus value . Particularly, the threshold value of in is set to 6.1, which has been accepted by more than 94% of experts [15]. Therefore, 13 evaluation sub-criteria are selected to realize the optimal site selection of vehicle charging station (Table 1 and Figure 1).

Table 1. Results of calculation of evaluation criteria based on FDM.

Perspectives	Initial sub-criteria	Pessimistic value		Optimistic value		Geometric mean		$M^i - Z^i$	Consensus value
		C_L^i	C_U^i	O_L^i	O_U^i	C_M^i	O_M^i		G_i
Economy development	Operating cash index	2	4	6	9	3.52	6.94	3.02	5.24<6.1
	Production value	1	5	6	8	4.97	7.54	4.46	6.26>6.1
	Profit ratio of sales	2	7	5	10	5.11	6.25	0.84	5.88<6.1
	Job creation	1	6	7	10	5.32	7.46	3.45	6.49>6.1
	Total asset turnover ratio	2	8	6	9	3.36	6.07	0.93	3.86<6.1
	Technology investment	2	6	7	9	4.35	8.7	2.32	6.53>6.1
	Total industrial output value	2	6	7	10	3.55	5.99	5.01	4.77<6.1
Energy utilization	Energy consumption	3	9	6	10	5.74	7.35	0.66	6.47<6.1
	Equipment utilization rate	2	5	7	9	3.75	5.68	5.32	4.72<6.1
	Water consumption	2	7	5	9	2.59	7.65	0.35	3.89<6.1
	Coal efficiency	2	6	7	10	4.59	8.59	3.51	6.54>6.1
	Oil consumption	1	5	7	8	4.05	6.28	2.74	5.16<6.1
	Auxiliary power ratio	3	4	8	10	3.54	5.24	7.59	4.40<6.1
	Water efficiency	2	6	8	9	4.35	7.85	3.16	6.10>6.1
	Steam loss	1	6	5	10	4.58	7.65	1.35	5.12<6.1
	Electric energy efficiency	2	6	7	10	5.06	7.64	2.36	6.35>6.1
Refuse recycle	Recycling revenues	1	6	5	9	3.54	7.24	0.76	4.18>6.1
	Waste water recycle	2	7	8	10	5.14	7.35	3.65	6.30>6.1
	Investment in green innovation technology	2	6	5	10	3.75	8.26	0.74	4.56<6.1
	By-product revenues	2	6	7	9	3.64	6.74	3.16	5.24<6.1
	Solid waste recycle	1	6	7	9	4.59	8.07	1.94	6.33>6.1
Pollutant emissions	Soot emissions	1	5	7	10	4.16	8.64	3.36	6.39>6.1
	Industrial soot emissions	1	5	7	10	4.35	6.87	5.11	5.52<6.1

	NOx emissions	3	7	6	10	5.89	7.68	1.32	6.35>6.1
	Fly ash emissions	2	7	6	10	3.74	8.14	0.96	4.44<6.1
	SO2 emissions	4	8	8	10	5.68	6.54	4.46	6.11>6.1
	Industrial noise	2	5	6	9	4.65	6.87	3.13	5.76<6.1
	Dust collection efficiency	3	8	7	10	3.75	8.96	0.06	4.78<6.1
	Denitration efficiency	1	8	7	9	5.56	5.98	2.02	3.09<6.1
	Effluent volume	3	7	4	9	4.21	7.64	-0.64	5.22<6.1
	Desulphurization efficiency	2	5	7	10	3.95	4.68	3.32	4.32<6.1

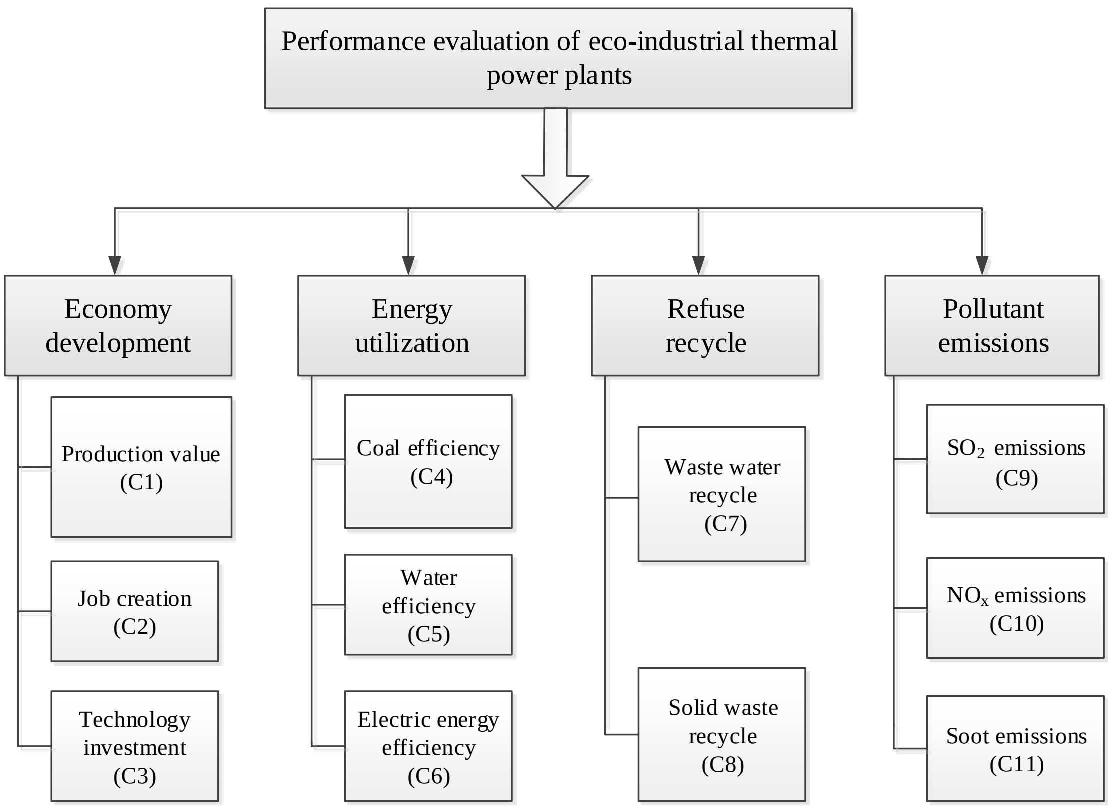

Figure1. Evaluation index system for eco-industrial thermal power plants

EXPLAINATION OF EVALUATION CRITERIA

In this section, the meaning of each evaluation criterion is explain and analyze, which can guide eco-industrial thermal power plants to manage the production processing and promote cleaner production.

Economy development

As other enterprises, the "economy development" criterion has also been drawn attention by eco-industrial thermal power plants. The criteria affiliated with the "economy development" aspect for performance evaluation of eco-industrial thermal power plants are summarized as below.

(1) Production value (C1): This criterion refelects the information of production added value and intermediate input. To be specific, the production added value comes from power generation, recycling utilization, energy saving and so on. And the all kinds of inputs constitute the intermediate inputs, such as raw material input, labor input and so on. Therefore, the "production value" criterion refers to the sum of enterprise added value and intermediate inputs.
(2) Job creation (C2): This criterion reflects the social benefit for employment of the eco-industrial thermal power plants. Since eco-industrial thermal power plants involves a long and complex industry production and value chain, the construction will promote the development of various related industries. Therefore, with the development of related industries, the employment of ETPPs and upstream and downstream firms will be promoted. The "Job creation" criterion in this paper refers to the social benefit of eco-industrial thermal power plants in employment.
(3) Technology investment (C3): This criterion reflect the technology performance in energy saving and emission reduction. So the new equipment update cost, technological installations cost and engineering services fee constitute the technology investment. The "technology investment" criterion refers to all investment in technology innovation of eco-industrial thermal power plants.

Energy utilization

The vital criteria affiliated with the energy utilization for performance evaluation of ETPPs are summarized below.
(1) Coal efficiency (C4): This criteria reflects the production information about the coal utilization, which refers to the coal consumption required by generating one kilowatt hours of electricity. This criterion is used to reflect the technical and economic efficiency of power generating equipment.
(2) Water efficiency (C5): This criteria reflects the water utilization information during the production process, which refers to the water consumption required by generating one kilowatt hours of electricity.
(3) Electric energy efficiency (C6): This criteria reflects the energy consumption of all equipment in an eco-industrial thermal power plant, which refers to the auxiliary power consumption rate of the whole eco-industrial power plant.

Refuse recycle

(1) Waste water recycle (C7): In the eco-industrial thermal power plant, the water recycle is very important to improve the energy saving performance. There are large amount of water resources are consumed in the power generation, which produces lots of waste water. Therefore, the waste water are recycled to saving water. The "waste water recycle" criterion measures the recycle capacity of waste water in an eco-industrial thermal power plant .
(2) Solid waste recycle (C8): As we all know, coal-fired power generation will produce a mass of coal ash and desulfurization gypsum. Therefore the thermal power plants will cause serious impact on the environment protection. In the eco-industrial thermal power plant, these solid waste are reused to produce plank, lime, and so on. This criterion measures the recycle capacity of solid waste in an eco-industrial thermal power plant.

Pollutant emissions

Large amount of gas pollutions are released during the power generation in thermal power plants. Among them, SO2, NOx and soot emissionss are selected as the key monitoring indicators by the "Pollutant emissions standard of thermal power plant" in China.
(1) SO2 emissions (C9): Refers to the SO2 emissions of per kWh electriticy powr of eco-industrial thermal power plants during the production process.
(2) NOx emissions (C10): Refers to the NOx emissions of per kWh electriticy powr of eco-industrial thermal power plants during the production process.
(3) Soot emissions (C11): Refers to the Soot emissions of per kWh electriticy powr of eco-industrial thermal power plants during the production process.

CONCLUSION

An evaluation index system for eco-industrial thermal power plants is presented based on circular theogy and fuzzy theory method. The initial evaluation criater are established based on circular economy theory, so the initial evaluation criteria contains of "Economy development," "Energy utilization," "Refuse recycle," and "Pollutant emissions" four aspects. And then, the fuzzy Delphi method is used to selected the final criteria, which containas of 13 sub-criteria, such as production value, job creation, electric energy efficiency, water efficiency, pollutant emissions and so on. This study provides a comprehensive and effective method for evaluation criteria selection of eco-industrial thermal power plants and also innovates the utilization of fuzzy Delphi method.

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