

The 6th International Conference on Applied Energy – ICAE2014

A Group Fuzzy Analytic Network Process to Prioritize Low Carbon Energy Systems in the Philippines

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Abstract

Low-carbon energy systems are being proposed as portfolio of solutions to mitigate CO₂ emissions from the electricity-generating power sector. Stakeholder's perception on such technology plays a crucial role in its successful implementation. Not only the technological and economic aspects, but also the environmental and social aspects that surround these technologies should be considered in determining which of these energy systems should be promoted, invested in, and subsidized. This decision problem should take into consideration the trade-offs due to several conflicting aspects involved in the prioritization. This paper thus proposes Fuzzy Analytic Network Process as a decision modeling tool in a group decision making environment to address the complexity of the decision structure and the uncertainty inherent in eliciting value judgments from stakeholders or experts. Fuzzy numbers are used to model the uncertainty, vagueness and incompleteness of information thus derived. The method then extends the fuzzy preference programming technique to derive the group priorities or weights from fuzzy pairwise comparative judgment matrices. A numerical example is presented to illustrate the proposed approach in prioritizing low carbon energy systems in the Philippines.

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Peer-review under responsibility of the Organizing Committee of ICAE2014

Keywords: CCS, renewable energy, nuclear energy, Fuzzy Analytic Network Process, MCDA, energy planning

1. Introduction

The power generation sector is known to be one of the major contributors of greenhouse gas emissions (GHG). In the Philippines, it is estimated that the total GHG emissions from the electricity generation would increase to at least 90 Mt in 2030 with an average carbon intensity of 0.54 kg CO₂/kWh based on the government's planned generation capacity installations for 2012-2030 [1]. Different climate change mitigating options (CCMOs) are recently being considered by the government to reduce the amount of GHGs released from the said sector. These include low-carbon energy systems such as fossil-based power plants with carbon capture and storage (CCS) technology, nuclear energy, and renewable energy.

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Prioritizing the energy alternatives is a challenging task that involves different factors and can be viewed as a multiple criteria decision problem in energy planning. This task should address the different perceptions of multiple stakeholders and several conflicting criteria due to the complexity of environmental, technological, economic and social aspects of the problem. Multi-criteria decision analysis (MCDA) techniques thus provide a systematic and transparent tool to assist decision makers in mapping out the problem and reach a justifiable well-informed decision. Many of these MCDA tools have been demonstrated useful to such complex energy-related decision problems [2-4]. For example, the Analytic Hierarchy Process (AHP), originally developed by Saaty [5], is one of the most widely used techniques found in the literature because of its operational flexibility and intuitive appeal. AHP decomposes the problem into a hierarchical structure and derives ratio-scale priority weights from pairwise comparative judgment matrices. Its generalization, the Analytic Network Process (ANP) is also now gaining popularity as this can address more complex decision structure incorporating network dependencies and interrelations among factors using the supermatrix approach [6-7].

In this paper, we present an MCDA technique for group decision making environment using fuzzy ANP to prioritize low carbon energy systems. Fuzzy numbers are used as linguistic scale to address the uncertainty and vagueness of judgments derived from a group of decision makers. The method then extends the fuzzy preference programming technique [8] to derive the group priorities or weights from fuzzy pairwise comparative judgment matrices. The rest of the paper is organized as follows. Section 2 gives an overview of methodology used here. Section 3 shows a numerical example to illustrate the methodology and Section 4 gives conclusions and future works.

2. Methodology

The procedure of the group fuzzy ANP is described as follows:

Step 1. Establish the hierarchical network decision structure [9].

Step 2. Elicit value judgment from decision makers for pairwise comparison matrices. The verbal representations of AHP's fundamental 9-point scale are modeled by triangular fuzzy numbers (TFN), for example, to account for vagueness and decision maker's degree of confidence as described in [9-10]. The group fuzzy judgment $\hat{a}_{ij} = \langle l_{ij}, m_{ij}, u_{ij} \rangle$ is computed from the aggregation of individual judgments of K decision makers using the weighted geometric mean as shown in the following equation:

$$l_{ij} = \left(\prod_{k=1}^K (l_{ijk})^{v_k} \right) ; m_{ij} = \left(\prod_{k=1}^K (m_{ijk})^{v_k} \right) ; u_{ij} = \left(\prod_{k=1}^K (u_{ijk})^{v_k} \right) \quad (1)$$

where the triple l_{ijk} , m_{ijk} , u_{ijk} represents the lower bound, modal value and upper bound of the TFN respectively, and v_k is the influence weight of the decision maker k .

The computed \hat{a}_{ij} then used as entry to the reciprocal pairwise comparison matrix \hat{A} of order n (i.e., the number of elements to be prioritized in a cluster) such that:

$$\hat{A} = \begin{bmatrix} \langle 1, 1, 1 \rangle & \hat{a}_{12} & \cdots & \hat{a}_{1n} \\ \hat{a}_{21} & \langle 1, 1, 1 \rangle & \cdots & \hat{a}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \hat{a}_{n1} & \hat{a}_{n1} & \cdots & \langle 1, 1, 1 \rangle \end{bmatrix} \quad \text{where} \quad \hat{a}_{ji} = \frac{1}{\hat{a}_{ij}} = \left\langle \frac{1}{u_{ij}}, \frac{1}{m_{ij}}, \frac{1}{l_{ij}} \right\rangle \quad (2)$$

Step 3. Compute the crisp priority vector w from \hat{A} of order n by approximating the solution ratios (a_{ij}) that would maximize λ [8,10], i.e., the highest degree of membership in a membership function of triangular fuzzy numbers indicating the intersection of degree of satisfaction of all computed ratios that would satisfy the initial fuzzy judgments obtained from at least $(n-1)$ out of the possible $(n-1)(n-2)/2$ pairwise comparisons. A positive λ indicates a consistent fuzzy pairwise comparison matrix wherein a $\lambda = 1$ suggests perfect consistency in preserving the order of preference intensities.

The proposed nonlinear programming (NLP) formulation to determine the optimal w is as follows:

max λ

subject to:

$$a_{ij} - l_{ij} \geq \lambda(m_{ij} - l_{ij}) \quad ; \quad a_{ji} - l_{ji} \geq \lambda(m_{ji} - l_{ji}) \quad (3)$$

$$u_{ij} - a_{ij} \geq \lambda(u_{ij} - m_{ij}) \quad ; \quad u_{ji} - a_{ji} \geq \lambda(u_{ji} - m_{ji})$$

$$\text{where } a_{ij} = \frac{w_i}{w_j} \quad ; \quad a_{ji} = \frac{w_j}{w_i} \quad \forall i = 1, \dots, n-1; j = 2, \dots, n; j > i$$

$$\sum_{k=1}^n w_k = 1; \quad w_k > 0$$

Step 4. Populate the supermatrix representation of the decision structure with normalized priority vectors. Overall priorities are then derived from the principal eigenvector of the said supermatrix normalized according to pertinent clusters. Please refer to [9] for the description of algorithmic details.

3. Numerical Example: Prioritization of low carbon energy systems in the Philippines

For this case study, an illustrative hierarchical network decision structure and its supermatrix are shown in Figure 1. The four main criteria are environmental (EN), economical (EC), technological (TE), and socio-political (SO) aspects. Alternatives are identified namely 1) decentralized power generation derived from renewable energy particularly hydroelectricity (HE), wind energy (WE), geothermal energy (GE), solar energy (SE), and biomass (BE); 2) Nuclear power plant (NE); and 3) Fossil fuel-based power plant with carbon capture and storage (FC). Details of pairwise comparison matrices were not discussed for the purpose of brevity. Only a sample of the numerical calculations was shown to demonstrate the proposed method particularly in computing group priority vectors from fuzzy pairwise comparative judgment matrices (PCJM). Figure 2 describes a sample incomplete pairwise comparison matrix containing only 7 fuzzy pairwise comparison judgments from the aggregation of equally weighted judgment of 6 decision makers/stakeholders from the academe, government and private sector. As in any AHP positive reciprocal matrix, the primary diagonal contains a crisp number of 1 in TFN notation $\langle 1, 1, 1 \rangle$. Using LINGO 14.0 to implement the NLP described in eqn.(3) for the said fuzzy judgments \hat{a}_{ij} , the preference weights of the energy alternatives with respect to environmental criteria (EN) were computed as follows ($\lambda = 0.73$): hydroelectric ($w_1 = 0.21$), wind ($w_2 = 0.28$), geothermal ($w_3 = 0.16$), solar ($w_4 = 0.17$); biomass ($w_5 = 0.13$); nuclear ($w_6 = 0.02$); and fossil fuel-based with carbon capture and storage ($w_7 = 0.03$). Accordingly, Table 1 summarizes the overall priorities of the alternatives computed from the principal eigenvector of the supermatrix described in Figure 1b. Results indicate that the most preferred low-carbon technologies are geothermal, wind and hydroelectric energy.

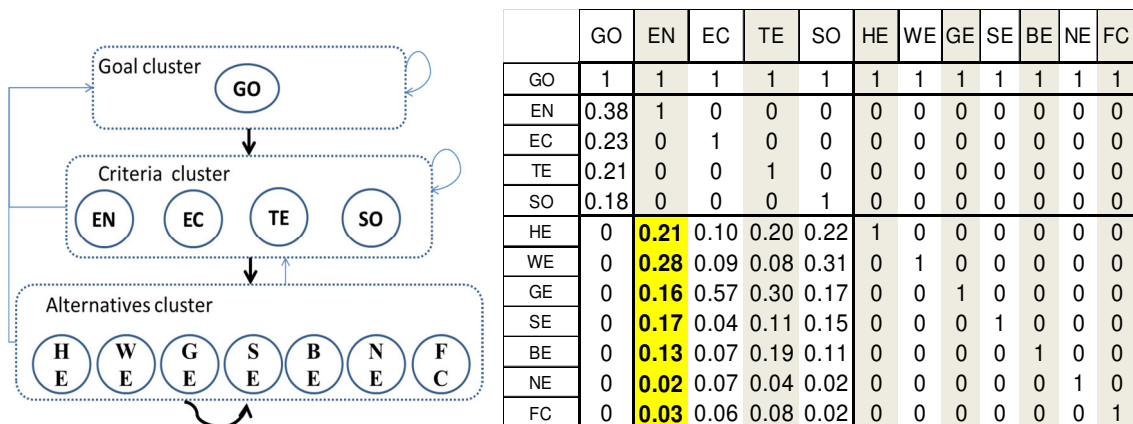


Fig.1. Sample decision structure (a) and its initial supermatrix (b)

(EN)	HE	WE	GE	SE	BE	NE	FC
HE	<1,1,1>	<0.65,0.79,1.07>					<5.03,6.32,7.46>
WE	<0.93,1.26,1.54>	<1,1,1>	<1.74,1.76,3.44>				
GE		<0.29,0.57,0.57>	<1,1,1>	<0.66,0.98,1.41>			
SE			<0.71,1.02,1.52>	<1,1,1>	<1.22,1.44,2.86>		
BE				<0.35,0.69,0.82>	<1,1,1>	<4.51,5.75,6.88>	
NE					<0.15,0.17,0.22>	<1,1,1>	<0.66,0.78,1.00>
FC	<0.13,0.16,0.20>					<1.00,1.27,1.51>	<1,1,1>

Fig.2. Fuzzy pairwise comparative judgment matrix for preference weights of alternatives with respect to environmental criteria

Table 1. Overall priorities and ranking of low carbon energy systems in the Philippines.

Energy alternatives	HE	WE	GE	SE	BE	NE	FC
Priorities	0.18	0.20	0.29	0.12	0.13	0.04	0.05
Ranking	3	2	1	5	4	7	6

4. Conclusion

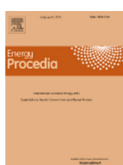
A group decision analysis technique using fuzzy ANP approach is developed and applied to prioritize low carbon energy systems in the Philippines. This approach enables to capture the complexity of interrelationship among factors involved in decision making while addressing the subjective value judgments of multiple stakeholders. The method can also derive crisp weights even from an incomplete fuzzy PCJM. Future studies would work on more complex decision structures with uncertainty analysis to determine the robustness of the proposed decision model.

Acknowledgements

The authors acknowledge the Commission on Higher Education- Philippine Higher Education Research Network (CHED-PHERNet) through its Sustainability Studies Program for financial support.

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Biography

Michael Angelo B. Promentilla is currently an Associate Professor at the Chemical Engineering Department of De La Salle University Manila, Philippines. He obtained his PhD degree in socio-environmental engineering at Hokkaido University, Japan. His research focuses on the development and application of multiple criteria decision analysis technique.