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A vague set fuzzy multi-attribute group decision-making model for selecting onsite renewable energy technologies for institutional owners of constructed facilities

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ABSTRACT

Institutional owners of constructed facilities are increasingly recognizing onsite renewable energy generation as an effective way of reducing their facilities' negative impact on the environment, lowering utility bills, and improving the institution's public image. Situations often arise when owners are uncertain as to which renewable energy technology (RET) to adopt for maximum benefit. Appropriate selection of a RET for institutional owners should consider multiple attributes such as cost, reliability, environmental impact, and institutional-wide factors. Additionally, individual decision makers' opinions from across the institution should be collected and aggregated into a group consensus opinion. This paper proposes a vague set fuzzy multi-attribute group decision-making model to select the most appropriate RET for institutional owners. The proposed model integrates group rational behavior theory with vague set fuzzy theory. The group rational behavior theory is utilized to account for the varying level of expertise and opinions of decision makers. The vague set fuzzy theory is utilized because most of the collected opinions from decision makers involve fuzzy data and information. The paper discusses the RETs that are evaluated with the proposed model followed by the factors affecting the selection process. Subsequently, the proposed model is described and illustrated using a case study.

1. Introduction

Energy production from traditional fossil fuel-based sources is a significant contributor to air pollution, releasing pollutants such as sulfur dioxide, nitrogen oxide, and carbon dioxide. These pollutants adversely affect human health and contribute to acid precipitation, smog, and greenhouse gases (GHG) emissions (US Green Building Council, 2009a). Renewable energy technologies (RETs) such as solar, wind, and biomass are environment-friendly and effectively reduces GHG emissions from building energy use. In addition, RETs can potentially reduce dependency on fossil fuels, lower the production of nuclear waste, and lessen the environmentally damaging operation of large hydropower dams. Furthermore, renewable energy projects can help reduce energy costs associated with lighting, heating, cooling, and operating buildings. As global competition for fossil fuels accelerates, the rate of return on RETs will continue to improve (NCHRP, 2011; US Green Building Council, 2009b).

Institutional owners who own and operate multiple constructed facilities with similar size, architectural and functional characteristics are increasingly recognizing onsite renewable energy generation as an effective means of reducing their facilities' negative impact on the environment, lowering their utility bills, and improving the institution's public image. Many such owners are implementing renewable energy projects for the first time and don't know how to best select the most appropriate technology. The fact that there exist numerous types of RETs only complicates the selection process. Conventionally, the task of selecting an appropriate RET is performed at individual project/facility level where only site specific conditions are considered. However, in the case of institutional owners, there are many economic and operational benefits associated with considering institutional-wide factors and selecting only a limited number of RETs to implement at the institutional level; these benefits include:

- Reducing procurement costs through economy-of-scale benefits associated with large purchases.
- Reducing engineering/design costs using standardized designs that

Abbreviations: RETs, renewable energy technologies; GHG, greenhouse gases; MCDM, multi-criteria decision making; ODOT, Ohio department of transportation; PV, photovoltaic; SAH, solar air heating; SWH, solar water heating; WT, wind turbines; GSHPs, ground source heat pumps; BHS, biomass heating system

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Nomenclature

U	a space of points
x	Any generic element in U
V	a vague set
t_V	a true membership function
f_V	a fake membership function
$t_V(x)$	the lower bound on the negation of x
$f_V(x)$	the lower bound on the grade of x
E	Set of decision-makers (experts)
e^k	a decision-maker (expert) in the set E
k	Index of decision-maker (expert) in the set E
d	Total number of decision-makers (experts) in the set E
R	Set of RET alternatives
i	Index of RET alternative in the set R
r_i	a RET alternative in the set R
n	Total number of RET alternatives in the set R
A	Set of attributes
j	Index of the attributes in the set A
a_j	An attribute in the set A
m	Total number of attributes in the set A
W	the fuzzy weight matrix
w_{kj}	the fuzzy weight of attribute a_j assigned by decision-maker e^k
p_{ij}^k, g_{ij}^{*k}, p_{ij}^{*k}, p_{wkj}, g_{wkj}^*, p_{wkj}^*	Vague values obtained from Table 1 that denotes 7-level language variable
B	the importance rating matrix of the group of decision-makers
b_{kk}	the importance score of the group of decision-makers given by decision maker e^k
b_k	the score of decision maker e^k in the group decision-makers
λ_k	the weight of decision-maker e^k
H	the fuzzy group decision matrix
e_{ij}	a comprehensive evaluation of the renewable energy technology r_i by group decision-makers
p_{ij}	$\sum_{k=1}^{d} p_{ij}^k \cdot \lambda_k$
p_{ij}^*	$\sum_{k=1}^{d} p_{ij}^{*k} \cdot \lambda_k$
w_j	the comprehensive distribution value of the attribute a_j by the group decision makers
p_j	$\frac{1}{d}\sum_{k=1}^{d} p_{kj}^k \cdot \lambda_k$
p_j^*	$\frac{1}{d}\sum_{k=1}^{d} p_{kj}^{*k} \cdot \lambda_k$
S	the fuzzy decision vector
S_i	a comprehensive evaluation of each RET
p_{S_i}	$\sum_{j=1}^{m} p_{ij} \cdot p_j$
$p_{S_i}^*$	$\sum_{j=1}^{m} p_{ij}^* \cdot p_j^*$
$Q(E(S_i))$	the final score of RET alternative i

need slight modification from one project to another.

- Reducing operation/maintenance costs since facility personnel has to be trained on operating/maintaining only a few selective RET systems.

The literature review has indicated that the success of a renewable energy installation depends on careful selection of the appropriate technology. Many owners who have not carefully selected renewable energy technologies have experienced several challenges including economic, operational, and/or environmental (Elzarka & Andrews, 2013). Therefore, appropriate selection of a RET should consider multiple attributes of available technologies including cost, reliability, and environmental impact. For institutional owners, the selection model should be able to collect and aggregate opinions from individual decision makers across the institution into a group consensus opinion.

Multiple criteria decision-making (MCDM) is the approach dealing with the ranking and selection of one or more alternative/s from a pool of alternatives. MCDM models are being widely used in the field of energy planning and renewable resource selection because of the flexibility these models provide to decision makers by taking many of the criteria and objectives into account. Several research studies have been conducted to develop MCDM optimization model for analyzing renewable energy sources. For example, RongGang Cong (2013) proposed a model to maximize the future generation of energy from renewable sources such as the wind, solar and biomass by combining a learning curve model with technology diffusion model and expectations about future economic development in China. In another study, a hybrid model was developed based on analytic network process to determine Turkey's energy status and prioritize alternative renewable energy sources (Kabak & Dağdeviren, 2014). In a similar study, an assessment model was developed using a multiperspective approach based on analytic hierarchy process (AHP) for energy planning and renewable resource selection (Salman & Razman, 2014). Kumar et al. (2017) mentioned in their research paper that in order to achieve the best solution that overcomes all environmental and local issues in real time application, MCDM model must be used in multiple criteria involving multiple scenarios. Despite the significant contribution of these previously mentioned studies, these studies mostly focused on single decision-making and did not consider group decision-making, and also focused on determining attribute weights and did not consider weights of decision makers, thereby assigning equal weights to every decision-maker. Since different decision makers may have varying level of knowledge, cognitive capacity, and experience, their opinions should be weighed accordingly. If equal weights are given to all decision makers it can negatively influence the final aggregated group decision. In this research paper, the weights of decision makers are determined based on the group rational behavior considering the colony characteristics of group decision to overcome and reduce ambiguity in preferences of decision makers. (Jianzhong and Jiuping, 2009; Jun & Wei, 2008).

It is relatively difficult to obtain exact numerical values for the criteria or attributes in RET selection process because the judgments of decision makers are usually vague, and their opinions are usually expressed in linguistic terms that are usually fuzzy and not exact. Several researchers have implemented fuzzy analysis to account for the vagueness associated with RET selection process. For example, Kyriakarakos, Patlitzianas, Damasiotis, and Papastefanakis (2014) designed and implemented fuzzy cognitive maps based on decision support toolkit for renewable energy systems planning, which was tested in Crete Island. In another study, a probabilistic multi-objective optimization model was developed for distributed energy resources planning in electricity networks including a wind turbine, photovoltaic, fuel cell, microturbine, gas turbine and diesel engine (Vahidinasab, 2014). Kahraman Kaya, and Cebi (2009) developed a multi-criteria decision-making methodology by using fuzzy axiomatic design and fuzzy AHP to select the best alternatives from a set of renewable energy sources. In another paper, an integrated fuzzy VIKOR and AHP methodology was used to determine the best renewable energy alternative for Istanbul (Kaya & Kahraman, 2010). A fuzzy multi-criteria decision-making method was developed to select the sustainable energy crop for the production of biofuels from agricultural biomass (Ligita, Dalia, & Tomas, 2013). Fuzzy AHP has been used in the selection of the best renewable energy source for electricity generation in Indonesia (Tasri & Susilawati, 2014). Fuzzy AHP was also used to determine the relative weights indicating the importance of energy security factors in China (Ren & Sovocool, 2014). The following points are inferred from the literature review conducted as part of this research: (1) Researchers can adopt fuzzy based modeling to enrich their research to arrive at